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ELECTROMAGNETIC RADIATION SIGNATURES FROM 0.2 TO 14.0 μm FOR TARGET AND BACKGROUND MATERIALS AND SCENE ENERGY SOURCES FOR NAVAL NIGHT SENSING

Patrick D. Fligor
Harold P. Zimmerman
James E. Hawkins

Technology Incorporated

FINAL TECHNICAL REPORT

July 1970

Prepared Under Contract N00039-69-C-1549,
Project XF52545002, Task RDT&E8065, for

Navy Department
Naval Electronics Systems Command
Washington, D.C. 20360

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FOREWORD

This study was sponsored by the Naval Electronics Systems Command, Munitions Building, Washington, D.C. The research was conducted by Technology Incorporated, 7400 Colonel Glenn Highway, Dayton, Ohio, under Contract N00039-69-C-1549, Project No. XF52545002 ("Long Range Night Viewing") and Task No. RDT & E 8065. Mr. Patrick D. Fligor, Head, Remote Sensing Section, was the principal investigator for Technology Incorporated. Mr. Carl Rigdon, Code 0514312, of the Components Section, was Contract Monitor for Naval Electronics Systems Command.

The research was entitled "Research and Investigation of Target Signature and Target Background Studies for Image Intensifiers." Research started in December 1968 and was completed in July 1970. The Air Force Avionics Laboratory, AVRS, cooperated in this study by allowing Technology Incorporated to utilize software and data generated by this contractor during three years of Target Signatures research and software development which has generated the Air Force's sensor system analysis version of the Target Signature Data Bank, which was originally developed by the University of Michigan under sponsorship of the Air Force Avionics Laboratory.

Cooperation of the Navy project office staff, the staff at AVRS, and members of those organizations cited in Table 1, "Data Sources," is hereby gratefully acknowledged. Gathering of many types of data from many diverse sources was performed by James E. Hawkins, Junior Research Engineer. Development of special graphical computer programs to manipulate data and generate charts on Calcomp plotters was performed by Harold P. Zimmerman, Scientific Programmer. The basic concepts of target signature analysis, data presentation formats, mathematical computation equations and the radiation physics were developed by Patrick D. Fligor, Principal Research Engineer. Other key personnel of Technology Incorporated engaged in this research were Miss Virginia L. Croft and Messrs. Arturo V. Serrano, Ronald G. Darner, John W. Kavanaugh, and William A. Lloyd.

ABSTRACT

To define the factors whereby Naval ships may detect, recognize, and identify military targets during night operations at sea, the reported research first assembled all available data describing the electromagnetic characteristics of each material comprising the target and background scene. Targets included ships, airplanes, and shore installations; and backgrounds included sea water, the sky, and shore materials. The scope of the study included the wavelength range from 0.2 to 14.0 micrometers, the world's temperate and tropical zones, and clear atmosphere conditions. After the principal illumination sources proved to be the moon, stars, nightglow, and tropospheric thermal radiation, the radiation of each was quantified into absolute values of radiometric units such as spectral irradiance in watts per square meter, and the total spectral energy of each on the earth's surface was calculated for horizontal and vertical surfaces. After the emittance and reflectance data for the most important target and background materials were collected, they were computer-standardized and -processed to yield Calcomp plots of reflectance and emittance versus wavelength. The results presented in this report serve as the first complete set of such data in one document. In addition, the Bibliography presents a computer tabulation of 639 documents pertinent to this study.

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LIST OF TABLES

1. Statement of the Problem

The goal of the research reported here was to define the factors whereby Naval ships may detect, recognize, and identify military targets during night operations at sea. The scope prescribed for this study included the wavelength range from 0.2 to 14.0 micrometers, the temperate and tropical zones of the world, and clear atmosphere conditions, but excluded countermeasure and camouflage factors. Existing published data were to be compiled and analyzed, and a bibliography of appropriate data sources was to be assembled.

2. Basic Approach

2.1 General

At the outset this study sought to assemble data describing the electromagnetic radiation characteristics of each material comprising the target and background scene. Targets are ships, airplanes, and shore installations; and backgrounds are sea water, the sky, and shore materials.

For the wavelength range from 0.2 to about 2 μm, the primary source of target information is the incident radiation reflected by target and background materials. And for wavelengths greater than 2 μm, the primary source of such information is the energy emitted by scene materials.

These information sources require several types of knowledge to predict the radiation levels entering the aperture of a sensor system. The target reflects spectral energy at short wavelengths and emits such energy at longer wavelengths. Consequently, this study assembled data which would describe each phenomenon across the spectrum considered. The atmosphere is a selective absorber of radiation across the given spectral range. In addition, the absorbing characteristics change with variations in the zenith angle. There are many energy sources to consider at night: nightglow, starlight, tropospheric thermal emission, moonlight, and others. To calculate the radiance entering the aperture, the best presently available data describing each phenomenon were assembled and then appropriate calculation techniques were developed to analyze all this data in one compatible system.

Essentially, the data sought were the factors affecting detection, recognition, and identification. To derive the data, a method was developed which would be useful throughout the spectrum and which would not impose limitations on the types of sensors analyzed. The study also intended to present the resultant techniques so that the user of this report could apply them to the parameters of any system to determine whether the signals entering the given system would be useful in detection, recognition, and identification.

After all available data were evaluated, the valid data were extracted, standardized by many different conversions, processed in formats convenient

for analysis, and categorized according to the standardizing and processing so that the reader could determine the applicability of the data for his own purposes.

2.2 Data Sources

All known sources for classified and unclassified data were contacted. These sources included libraries for published literature as well as government, university, and industrial organizations for any type of data they could provide. The organizations listed in Table 1 were contacted to request data. Although surprisingly few could offer substantial data, and many likely sources had none, sufficient data were eventually acquired to permit analyzing the spectral factors affecting naval night sensing. As a result, a library of 639 documents was assembled, as listed in the bibliography.

2.3 User Assumption

In the preparation of the data for this report, it was assumed that the user would be familiar with the basic methods dealing with electromagnetic radiation in the 0.2 to 14.0 μm range of the spectrum. In any event, these methods can be found in the sources cited as references. In addition, L. M. Biberman of the Institute for Defense Analysis has published through the years a series of reports (References 1 through 7) which provide insight into the problems of analyzing this part of the spectrum in consistent quantitative radiometric units.

3. General Description of the Sensing Situation

The sensor to be analyzed is a ship- or airplane-mounted device which operates over the sea at night with no illuminator. With clear sky conditions assumed and the entire spectrum from 0.2 to 14.0 μm considered, image intensifier wavelengths near 1 μm are stressed primarily. Targets could be ships, airplanes, or shore installations viewed against expected backgrounds.

This study primarily emphasized the generation of data which would realistically describe real-world constituents of the given scene: ships and aircraft, the sea and sky, and land materials near the shore. Additional special data was required to describe the energy sources at night and the atmospheric effects.

The function of the sensor system is to convert electromagnetic energy into a display image for human observation. If the displayed information has the proper contrast and resolution of detail, the observer can detect, recognize, or identify the target among the background.

Data from this report can be used to describe the input signals entering the aperture of the sensor system. Given the signal processing parameters of a sensor system along with this data, the reader can determine what the system output will be for this input from realistic target scenes.

TABLE 1

Organizations Contacted for Basic Data

Air Force Avionics Laboratory
Wright-Patterson Air Force Base, Ohio
Attn: AVRS

Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151
Attn: Dept. A

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314

Esterowitz, Leon, Dr., Consultant
5616 Bloomfield Dri.
Alexandria, Virginia 122316

Foreign Technology Division
U.S. Air Force
Wright-Patterson Air Force Base, Ohio
Attn: Lt. DiLorenzo

Honeywell Corporation
Hopkins, Minnesota
Attn: Mr. Paul Kruse

Infrared Countermeasure Branch
Naval Ordnance Test Station
China Lake, California
Attn: Mr. George Linsteadt, Code 3051

Institute for Defense Analysis
Army-Navy Drive
Washington, D.C.
Attn: Mr. L. Biberman

IR Background and Atmospheric Physics Specialty Group
& IRIA Data Center
University of Michigan
Ann Arbor, Michigan
Attn: Dr. S. Harris, Jr., Chairman

IRIA Data Center
University of Michigan
Ann Arbor, Michigan
Attn: Miss Mildred Denecke, Manager

Kitt Peak Naval Observatory
950 N. Cherry Avenue
Tucson, Arizona
Attn: Dr. Joseph W. Chamberlain

National Aeronautics and Space Administration
P.O. Box 33
College Park, Maryland 20740
Attn: Scientific and Technical Information Facility

Naval Civil Engineering Laboratory
Naval Facilities Engineering Command
Port Hueneme, California
Attn: Dr. Haynes

Naval Ordnance Test Station
China Lake, California
Attn: Mr. Peter Leet, Detection Branch

Naval Scientific and Technical Intelligence Center
Washington, D.C.
Attn: Mr. Synder, Code 30

Naval Scientific and Technical Intelligence Center
Washington, D.C.
Attn: Mr. Nelson, Code 241

Naval Ship Research and Development Center
Annapolis, Maryland
Attn: Mr. Mel Greenberg

Remote Area Conflict Information Center
Battelle Memorial Institute
Columbus, Ohio
Attn: Mr. James Purdy

Target Signature Analysis Center
Willow-Run Laboratories
University of Michigan
Ann Arbor, Michigan
Attn: Mrs. Diane Earing

U.S. Army Natich Laboratories
Natich, Massachusetts
Attn: Mr. Alvin O. Ramsey

U.S. Army Night Vision Laboratory
Fort Belvoir, Virginia
Attn: Mr. John Johnson

U.S. Naval Reserve Training Center
Gettysburg Road
Dayton, Ohio
Attn: Lt. Comdr. Westall

U.S. Naval Research Laboratories
Washington, D.C.
Attn: Dr. Henry Shenker

U.S. Navy Liaison Office
Wright-Patterson Air Force Base, Ohio
Attn: Comdr.

4th Naval District
Philadelphia, Pennsylvania
Attn: Lt. Comdr. Parks, Code 32

4th Naval District
Philadelphia, Pennsylvania
Attn: Lt. Comdr. Fugate, Intelligence Office

4. Definition of Detection, Recognition, and Identification

The differences between detection, recognition, and identification are primarily a function of resolution, more detail being required for recognition than detection and more for identification than recognition. For any of the three operations, the sensor must receive a signal which is detectable because it is at a wavelength and level within the sensor's capability.

5. Detection

Detection may be defined as the process of determining the presence of something. For naval targets, this would be an unexpected ship or airplane. A ship, for example, would first be detected close to the horizon, depending upon the detection range of the sensor and the existing weather and illumination conditions. The important factor is how the radiation characteristics of the ship would differ from those of the background.

Let us consider the case where a ship is very far away, but not obscured by earth curvature. Assume that the ship subtends less than the entire volume of one round resolution element, as illustrated in Figure 1.

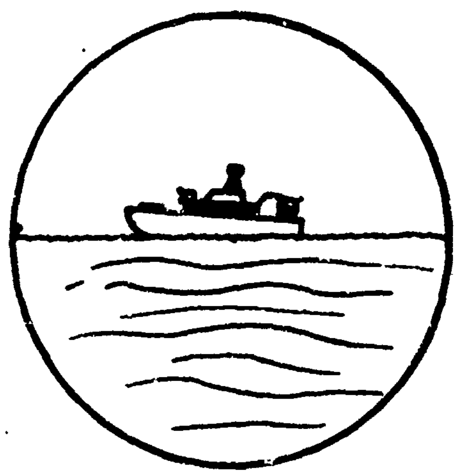


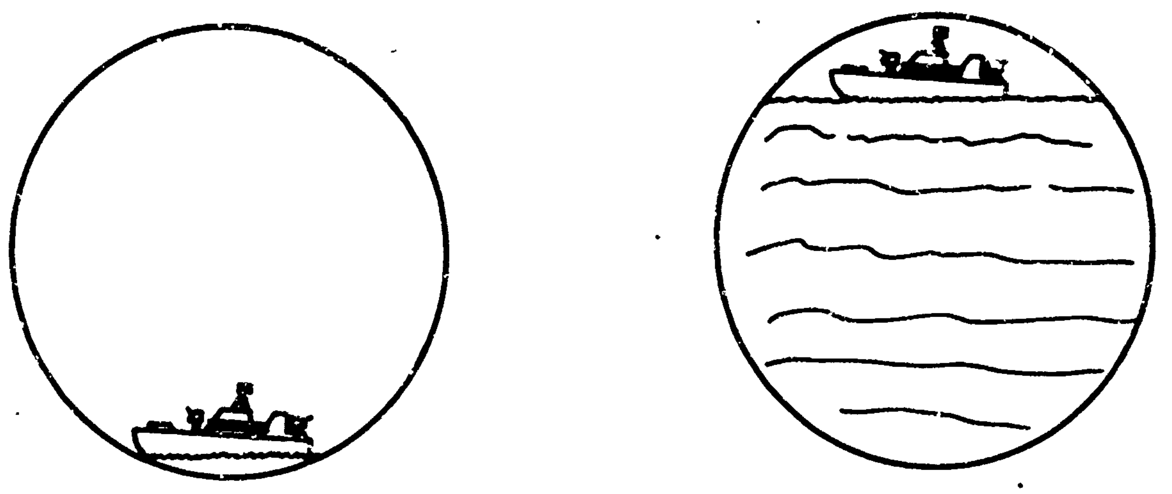
Figure 1. Distant Ship in Center of Scene

As a sensor scans this scene, its detection of the ship depends upon the sensitivity of its detection threshold, which is set according to the signal levels generated by the background and any target within the field of view. Figure 2 shows two other examples of the ship in the background scene where the scan-line elevation changes the background considerably.

5.1 Detection Thresholds

If a ship was not present, the scene could be all sky, all water, or any combination of these within the scan geometry of the given sensor. To maximize the probability of target detection, the threshold is adjusted to minimize false alarms and false dismissals. The sensor mounting and field-of-view

define the vertical limits of the scan. The radiation characteristics of both sky and sea change with sensor elevation angle. A larger range of elevation angles not exceeding the background threshold requires widening the tolerance band encompassing the detection threshold levels. All the above factors vary with wavelength. The optimal selection of detection thresholds should be made easier and more quantitative by using the data and techniques reported in this document.



a. scanner high

b. scanner low

Figure 2. Distant Ship with Scanner High and Low

5.2 Signal Changes vs Scan Position

Assume the scan raster is such that the single resolution element scans from top to bottom. From the top of the scan to slightly above the horizon, it sees the night sky. Next it views the top of a ship mast and then sees a scene similar to that in Figure 2a. Thereafter, it views in order the configuration in Figure 1, the scene in Figure 2b, and finally all water. As this scan progresses, the detection will be governed by a measure of the relative output of the sensor when the ship is present and when it is not. This procedure is somewhat analogous to the study of signal-plus-noise to noise ratios in detection theory. However, we are here concerned with the ratios for ship plus background versus background alone (see Figure 3).

The sensor could detect the ship the instant the top of the mast enters the resolution element if the mast generated a large enough signal change. If it did, the output display would appear as if the entire cell were filled with a target, since this element offers the finest resolution of the system. Further scanning would continue to indicate a target until its signal fell below the detection threshold. Of course, there are several sensor systems whose detection processes vary: Some systems contain multiple thresholds and some are based upon principles of signal correlation. The threshold levels can be varied by some systems based upon time, position, or supplementary sensor information such as area integration as utilized by automatic camera exposure controls.

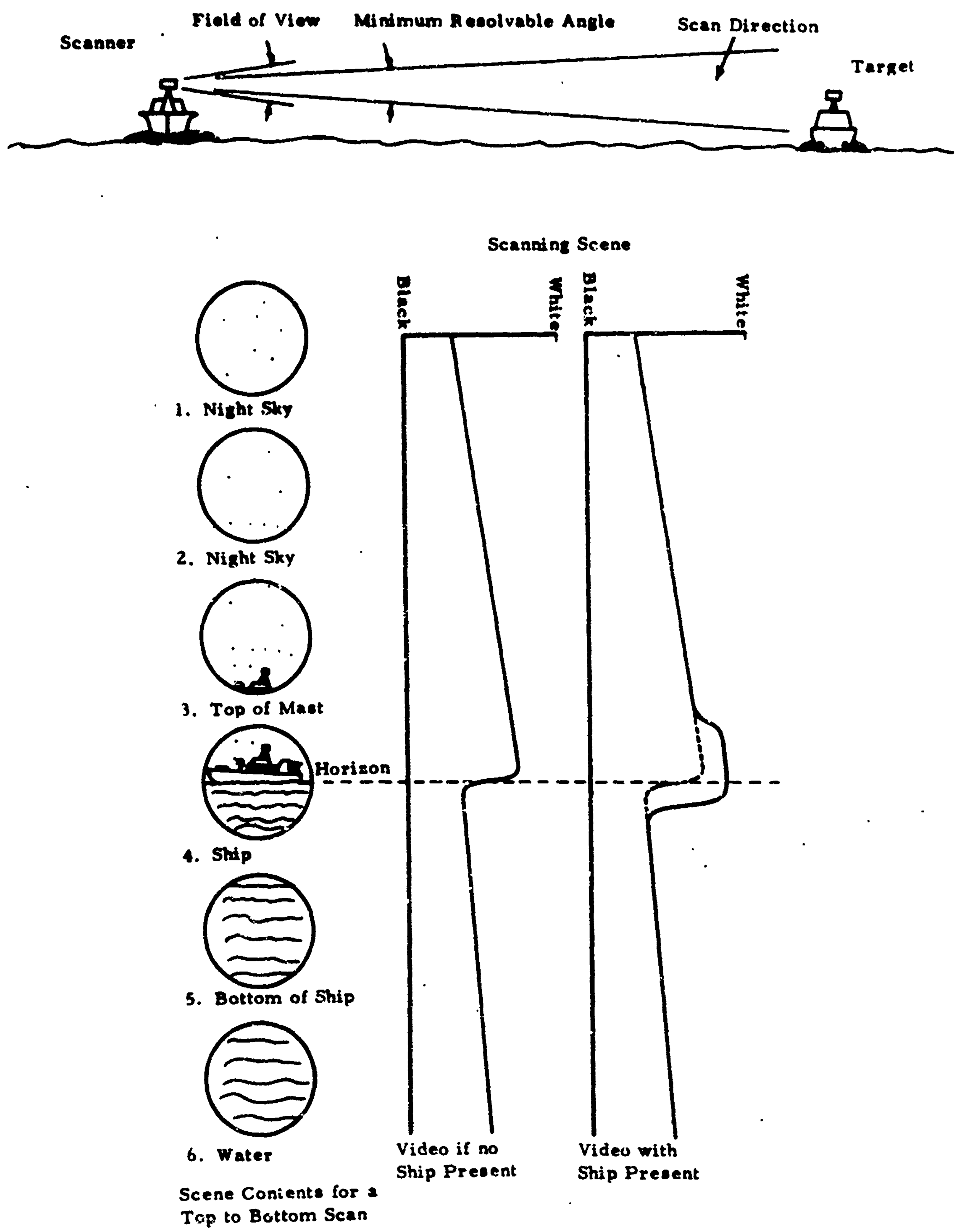


Figure 3. Diagram Describing Sensor Considerations

5.3 Electrical System Detection

A sensor system converts optical energy to electrical energy, which is amplified and then processed by a detector to generate a target signal. For a given system, the process of amplification, noise sources and levels, detector characteristics, and threshold levels must be specified. Given this information, the sensor observer can identify the changes in detector output levels that electrically indicate the presence of a target. At the scene, the energy radiated toward the detector may be expressed mathematically as follows:

$$J_\lambda = \sum_{i=1}^{n} A_i \cdot D_i \cdot (N_\lambda)_i \qquad (w/sr) \qquad (1)$$

where

i = index of constituents in field of view

A_i = area of ith scene boundary

D_i = directional radiation factor for ith boundary's orientation

$(N_\lambda)_i$ = radiance of ith constituent material

Then the detector electrical output would be

$$P = \int_\lambda \int_\Omega J_\lambda \cdot \tau_\lambda \cdot T_\lambda \cdot d\Omega \cdot d\lambda \qquad (w) \qquad (2)$$

where

Ω = steradians

T_λ = transducing factor of detector system

τ_λ = atmospheric transmission between scene and sensor

If no ship is present, then the entire field-of-view is filled with background.

In that case,

$$A_{\text{resolution element}} = A_{\text{sky}} + A_{\text{water}} \qquad (3)$$

If a ship is present, then

$$A_{\text{resolution element}} = A'_{\text{sky}} + A'_{\text{water}} + A_{\text{ship}}, \quad A' \leq A. \qquad (4)$$

The data in this report is used as follows to analyze the detection process. The power input, dH/dA, to the sensor is calculated as a function of range for each material on the basis of material area. The reader will supply the areas for each scene constituent. Multiplying dH/dA by the scene material area and by the aperture size will yield the spectral power, P_λ, entering the aperture for that scene constituent. After P_λ has been calculated for each constituent, the P_λ's should be added to yield the total spectral power entering the aperture, P_λ, for the entire scene. Then this total should be combined with the system response to calculate the electrical outputs.

The target will be detected when the electrical outputs exceed the detection threshold. Several aspects of the radiation could cause the detection. If the ship radiates much more or less energy than the background, then the scene area should be smaller to produce a threshold crossing. For convenience, this relationship is plotted in Figure 4 where the radiance change for the sensor is calculated for various parts of the area subtended by the target (Δ area) when the radiance change is known as the scanner leaves the b--kground and crosses the target boundary. Changes in radiation (sometimes c- ed contrast) can be caused by differences in reflectance, emittance, temperature, changes in illumination, and changes in the sensitivity of the detector across the spectrum. Weather changes can also vary the spectral pattern at the detector for the same scene.

5.4 .culation of Detection Range

Knowledge of the threshold characteristics and the spectral detectivity (such as D*) will permit defining the sensor characteristics. To calculate the spectral power, P_λ, the spectral irradiance for the target and background materials may be used to define the power densities of these materials at the sensor as a function of range and size. Properly combining the spectral detectivity with the spectral power for each material will yield the two detector output values for the target and background materials. The ratio of the two values is calculated as

$$\Delta 0 = \frac{0_{Target} - 0_{Background}}{0_{Background}} \qquad (5)$$

If $\Delta 0 > 0.0$, the target radiates more power than the background. The detector threshold at the base signal level of the background defines the signal increase which the detector needs to electrically identify a target, Δ DET. In Figure 4, Δ0 values are plotted along the abscissa with Δ DET values on the ordinate. The intersection of a given two values defines a Δ area, which is the minimum portion of the resolution element which the target material must occupy to permit detection. Given the size of a ship and the angles of the minimum resolution element, a calculation based upon geometry will yield the range.

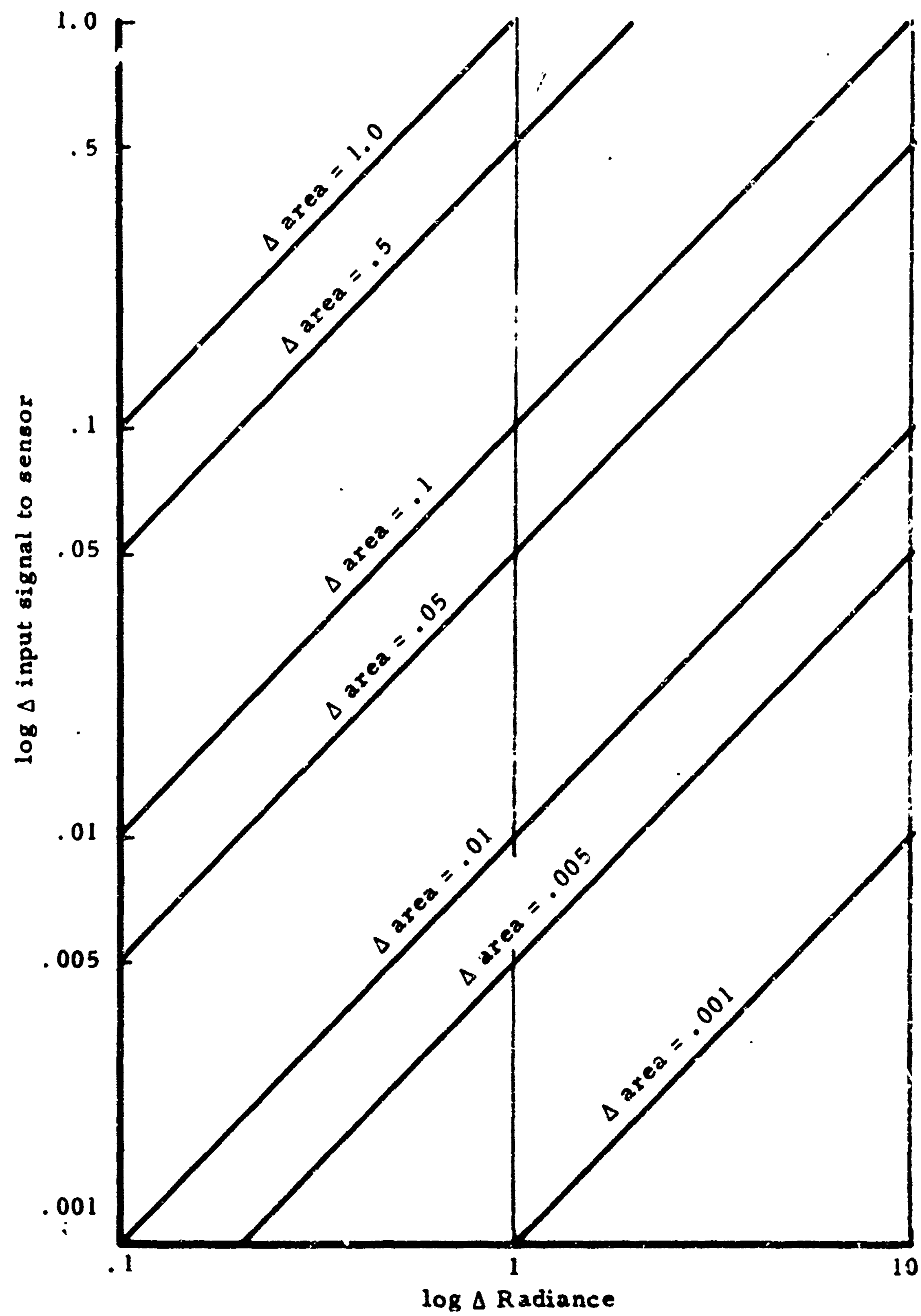


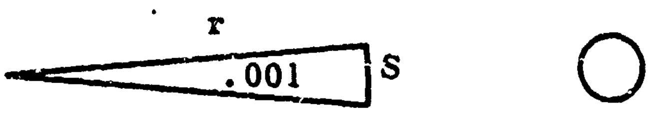
Figure 4. Relationship Between Power Received to Radiance Change Between Background and Target for Various Portions of the Resolution Element Being Target (Δ area)

5.5 Detection Range Example

A P6 class torpedo boat, for example, presents approximately 270 square feet of cross-sectional area when approaching the sensor. For the spectrum used, assume that the change in radiance affects the output by 10%. Then,

$$\Delta 0 = \frac{1.1 - 1.0}{1.0} = 0.1 \qquad (6)$$

If the detector required a 5% change to identify a target, then from Figure 4 the Δ area equals 0.5, or the ship should subtend one-half of the field-of-view (where the entire field-of-view is 270 ft^2 x 2 = 540 ft^2). Assuming that the resolution is 1 milliradian in a circular pattern gives



$$a \approx \frac{\pi S^2}{4}$$

$$a \approx \frac{\pi S^2}{4} = \frac{\pi \times r^2 \times 10^{-6}}{4} = 540 \text{ ft}^2 \qquad (7)$$

$$r^2_{det} = \frac{540 \text{ ft}^2 \times 4}{\pi \times 10^{-6}} = 6.86 \times 10^8 \text{ ft}^2 \qquad (8)$$

and

$$r_{det} = 2.62 \times 10^4 = 26,200 \text{ ft} \qquad (9)$$

To see the P6 waterline on the horizon, the sensor should be approximately 16-1/2 feet above the water, as read from Figure 5.

If the P6 were being viewed from the side with a circular resolution element, the detection range would be different. At the bow, which would be raised up when planing, one-half of the circle would be filled as shown in Figure 6. In this illustration, the diameter of this circle is approximately 28 feet with

$$\text{area} = \pi \cdot 14^2 = 616 \text{ ft}^2 \qquad (10)$$

$$(\text{range}_{det})^2 = \frac{616 \times 4}{\pi \times 10^{-6}} = 7.84 \times 10^8 \text{ ft}^2 \qquad (11)$$

and

$$\text{range}_{det} = 28,000 \text{ ft} \qquad (12)$$

From Figure 5, the sensor should be 18 feet 10 inches above the water.

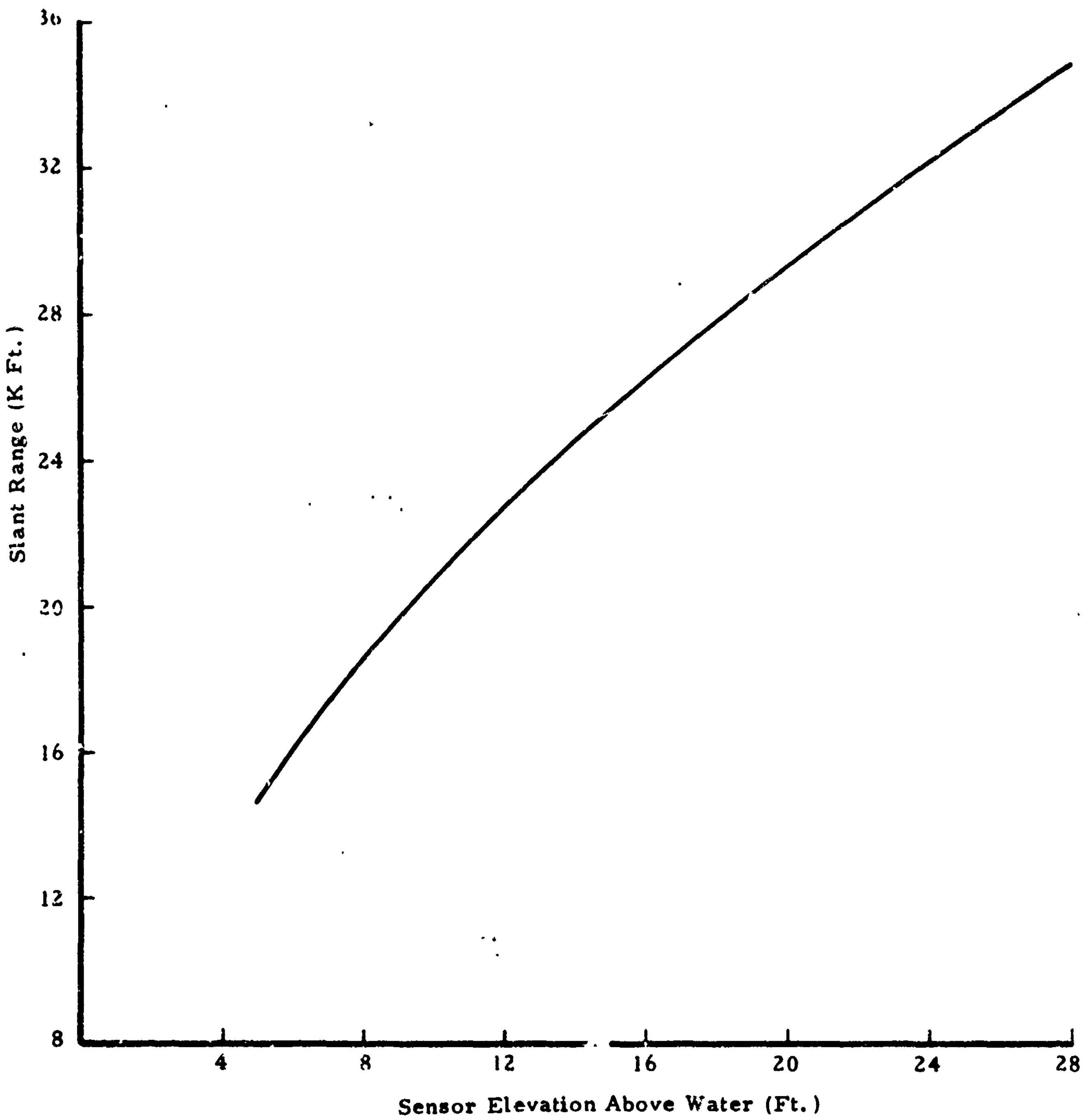


Figure 5. Effect of Earth Curvature on Range to Sea Target Waterline

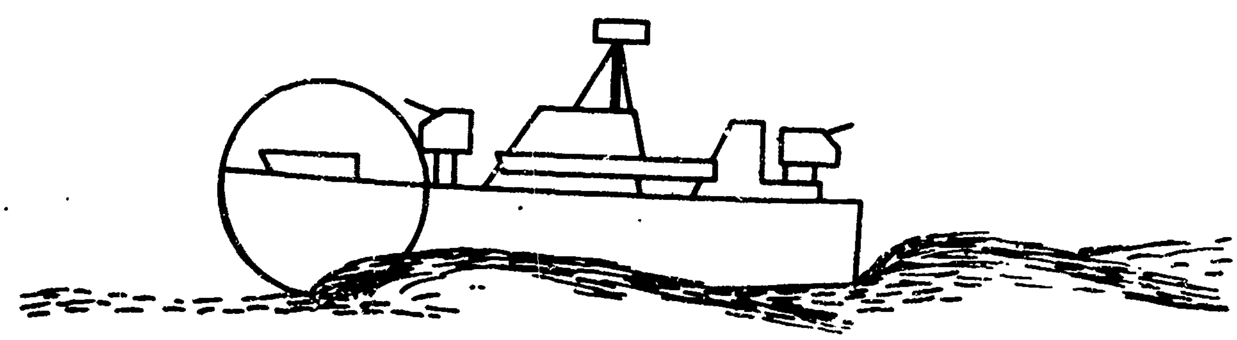


Figure 6. Circular Aperture Scanning a Fast Torpedo Boat from the Side

6. Recognition

An observer recognizes a target after he has detected it. Recognition may be defined as the perception of an object type with characteristics previously known. At sea, recognition would constitute the perception that a detected object, for example, is a ship. Alternative recognitions might be a low-flying airplane, a cloud on the horizon, a peculiar wave pattern, or a surfaced whale or other large fish, as shown in Figure 7. If these four alternatives can be eliminated, and detection is reliable, then the detected object must be a ship. These alternatives might be eliminated by determining the spectral radiation pattern at the minimum detection range for the weakest spectral sensitivity of a multiband sensor, regardless of the spatial resolution. In that case,

$$\text{Range}_{\text{recognition}} = \min_{i=1,\ldots,K} (\text{Range}_{\text{detection}_i}) \tag{13}$$

for K channels.

Figure 7. Example of Possible Items Detected as Targets

If a spectral test cannot eliminate the other possible targets, then the shape and size of each object (as shown in Figure 7) must be considered for a spatial test. Then the display pattern of each object should be calculated for each expected target azimuth angle at the maximum detection range. If the display patterns all differ, then the recognition and detection of an object could be simultaneous. If two or more objects have the same display pattern, then the resolution must be increased (by decreasing the range) until the pattern of each object may be distinguished from those of other objects. In summary, the resolution required for recognition is a function of the shape and spectral radiation pattern of the set of possible targets plus possible false alarms

7. Identification

Identification may be defined as the process of establishing the sameness of essential or uniquely grouped characteristics. For ship targets, identification would classify the ship, for example, as a P4, P6, P8, or Komar. Both resolution and contrast must be adequate.

7.1 Resolution Requirements

The resolution required for identification is a function of the characteristics of the objects comprising the set of possible targets. Basically, something akin to the profile or three views must be evaluated. To separate one ship from another requires that some unique pattern be detectable. Suppose the only difference between two candidates is a gun turret mounted on the bow. Initially, the resolution must be fine enough to permit the observer's determining the presence of the turret. In some instances, the turret definition may be poor at the resolution required to identify it as being present. Identification, therefore, is a process similar to detection, except that the goal is to find a unique identification cue once the target is detected. The resolution must be such that this cue is discernible to the observer.

7.2 Contrast Requirements

Assuming that the resolution is adequate for identification, the target contrast with the background must be next considered. To discern some difference between the spatial characteristics of a target, the observer must have some minimum contrast between the target and the background. Since the background within the scene can change, we must carefully consider the contrast at all the points along the boundary between target and background. Although the contrast could be inadequate at certain boundary points with no loss of information, it must be adequate at the critical boundary locations, such as those around the gun turret in the preceding example. The scan pattern and the shape of the resolution cell will affect the definition of where the contrast must be high and of how much contrast must exist for detection of the identifying cue. Each target-background combination must be evaluated from all aspect angles with typical scan geometries to arrive at statistically acceptable performance for the tactical approach angles in a given surveillance situation.

Fundamentally, the signal to be detected is the product of the energy difference per unit area of the cue feature, the cue feature subtended area, and the directional radiation coefficient. The energy difference in this product is related to contrast. This product will modulate the existing signal without the cue, the difference being the signal plus the background. Then the target will be identified if the difference between the signal plus the background and the background alone is great enough to cross the human or machine detection threshold. Figure 4 shows the quantitative definition of these relationships.

8. Electromagnetic Radiation Effects

Many physical effects govern the signals entering a sensor aperture. These signals are basically electromagnetic energy in the form of spectral irradiance patterns. These patterns are caused by any mechanism which can generate energy within the 0.2 to 14.0 μm wavelength range. Radiation starts

with basic sources such as the sun or other heat sources and is modified by every material that occupies the path between the energy source and the sensor aperture.

For night viewing, the principal energy sources are the moon, stars, nightglow, and tropospheric thermal radiation. In this wavelength range the primary constituents of the atmosphere which affect transmission are water vapor, carbon dioxide, ozone, and scattering particles. The scene materials reflect incident energy and emit energy caused by the molecular motion due to the temperature of these materials.

8.1 Spectral Effects

Each of the above phenomena varies with the radiation wavelength. Also the existing physical parameters for the radiation paths will modify the patterns. Figure 8, a plot reproduced from Reference 8, p. 16-2, shows many interesting aspects of radiation. Note that the abscissa variable is wavelength, and the ordinate is irradiance. The 5900° K blackbody curve illustrates the characteristic shape of all blackbody curves. Note that the curve for the sun's irradiance is not exactly a shape characteristic of a blackbody. The difference between the sun's irradiance at the top of the atmosphere and at sea level is caused by the selective atmospheric absorption of energy at different wavelengths.

Examples of the atmosphere's selective absorption are shown in Figure 9, which is from p. 10-3 of Reference 8. These curves indicate the spectral effects of atmospheric transmission.

The real-world variability poses the greatest difficulty in characterizing these phenomena. Any of the constituents can vary considerably over the spans of time and place that must be analyzed. Therefore, the study must deal with trends which can be calculated from model conditions such as those given in the US Standard Atmosphere (References 9, 10). Other effects must also be modeled by using reasonable estimates for average conditions. Since the reflectance of each material will vary somewhat, average values must be calculated to represent the nominal reflectance of each material.

8.2 Energy Sources

Energy sources for night sensing include the moon, starlight, nightglow, and tropospheric thermal heating. Figure 10 from Reference 11, p. 35, shows the spectral energy from the moon and various planets. Of course, to be a factor, the moon or planet must be above the horizon and illuminating the given scene. Note that these curves are calculated and represent the spectral irradiance outside the atmosphere, not that at the earth's surface.

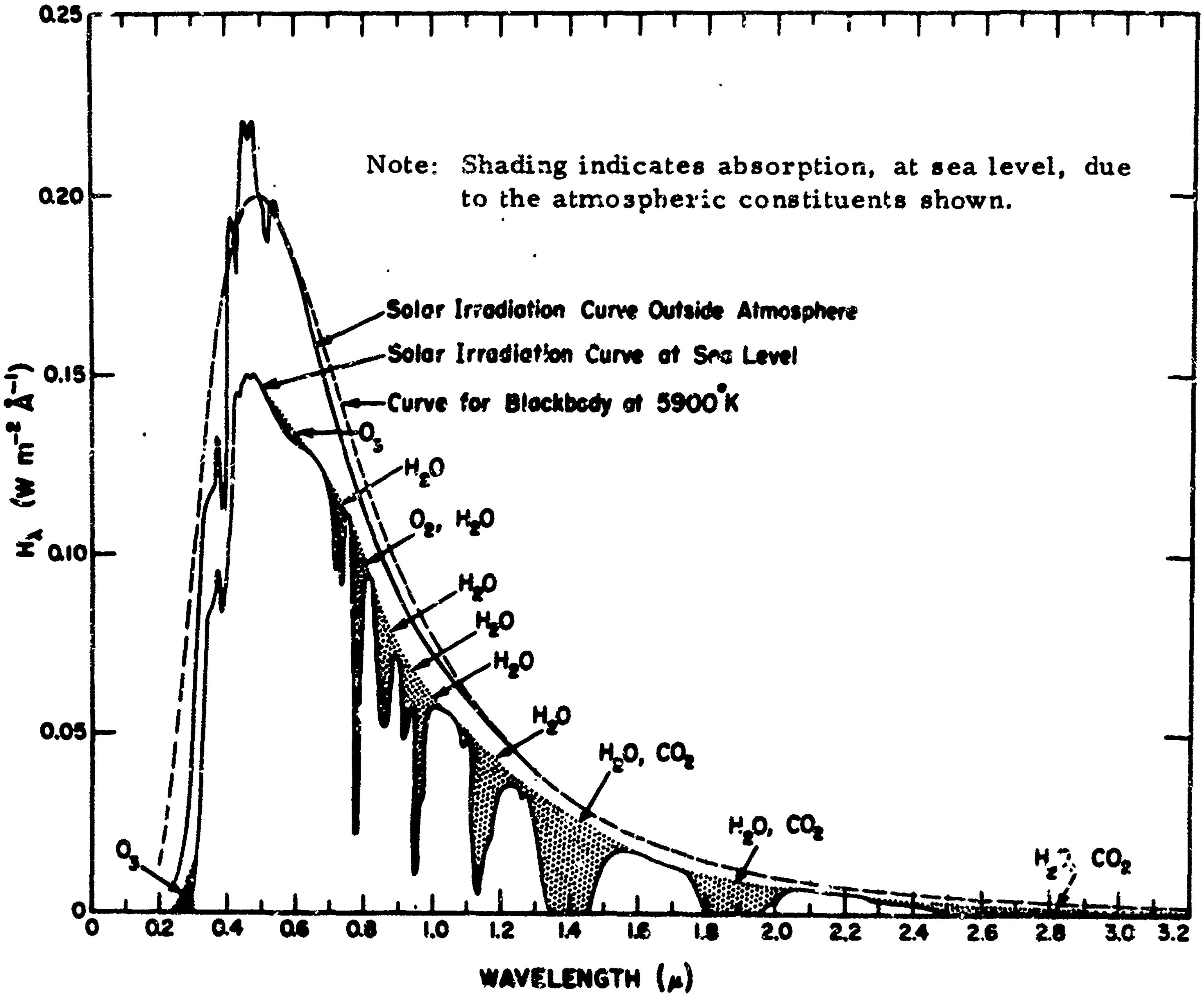


Figure 8. Spectral Irradiance of the Sun (Reference 8)

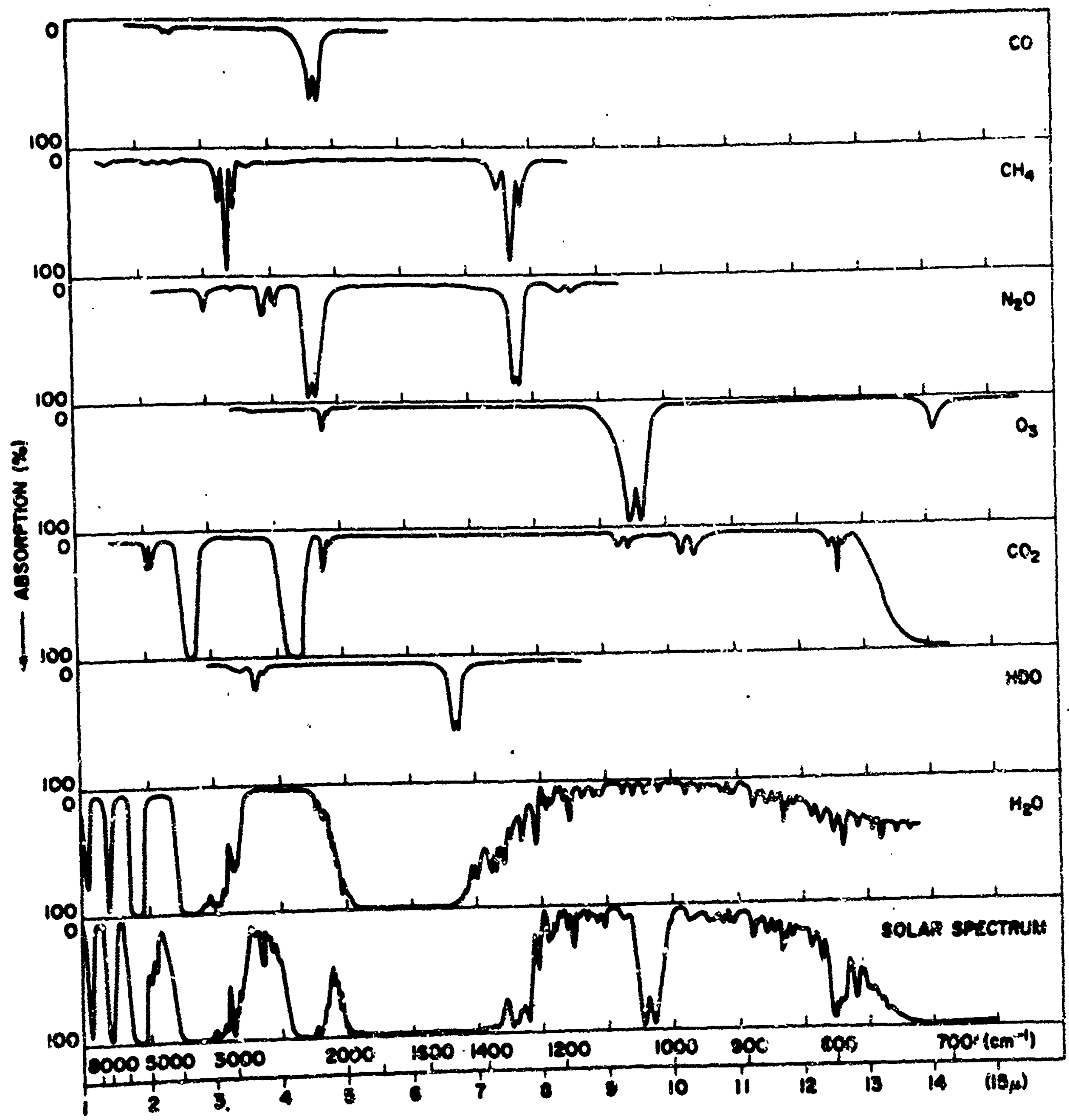
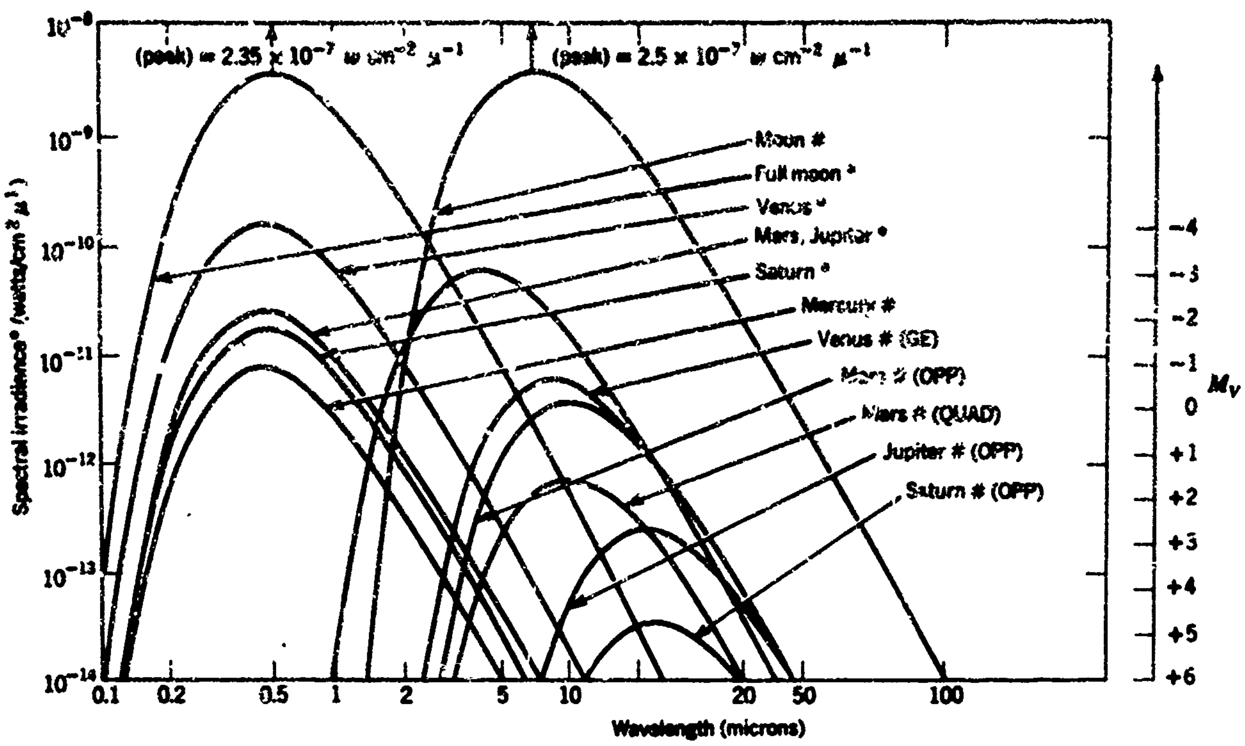


Figure 9. Spectral Absorption of Atmospheric Constituents and the Solar Spectrum (Reference 8)



Note: * = calculated irradiance from planets, at brightest, due to sun reflectance only;
GE = inferior planet at greatest elongation;
OPP = superior planet at opposition;
QUAD = superior planet at quadrature;
# = calculated irradiance from planets due to self-emission only.
M_V = visual magnitude at maximum spectral irradiance.

Figure 10. Calculated Spectral Irradiance from Planets at the Top of the Atmosphere (Reference 11)

There are one billion visual stars, according to Russell, Dugan, and Stewart in Reference 12. On page 622, they list the numbers for the magnitude of each star, as reproduced in Table 2. On page 626, these authors state that more than 99% of the stars fall into six spectral classes. Their distribution is shown in Table 3, which was taken from Reference 12, p. 626. The spectral irradiance for various population levels of stars above the atmosphere is shown in Figure 11, which was extracted from Reference 13.

The tropospheric thermal radiation shown in Figure 12 is based on measurements by Fredrickson, Gushing, and Paulson and by Bell, et al, as given in Reference 14, p. 25. This data is taken at the earth's surface.

TABLE 2

Number of Stars Brighter Than a Given Magnitude (Reference 12)

Magnitude Limit	Number of Stars Photographic	Visual	Magnitude Limit	Number of Stars Photographic	Visual
4.0	360	530	13.0	2,720,000	5,700,000
5.0	1,030	1,620	14.0	6,500,000	13,800,000
6.0	2,940	4,850	15.0	15,000,000	32,000,000
7.0	8,200	14,300	16.0	33,000,000	71,000,000
8.0	22,800	41,000	17.0	70,000,000	150,000,000
9.0	62,000	117,000	18.0	143,000,000	296,000,000
10.0	166,000	324,000	19.0	275,000,000	560,000,000
11.0	431,000	870,000	20.0	505,000,000	1,000,000,000
12.0	1,100,000	2,270,000	21.0	890,000,000	

TABLE 3

Percentage of Stars of the Various Spectral Classes (Reference 12)

Visual Magnitude	B (B0 to B5)	A (B8 to A3)	F (A5 to F2)	G (F5 to G0)	K G5 to X2)	M (K5 to M8)
Brighter than 2.24	28	28	7	10	15	12
2.25 to 3.24	25	19	10	12	22	12
3.25 to 4.24	16	22	7	12	35	8
4.25 to 5.24	9	27	12	12	30	10
5.25 to 6.24	5	38	13	10	28	6
6.25 to 7.24	4	30	12	14	33	7
7.25 to 8.24	2	26	11	16	37	8
8.25 to 9.24	1	27	10	21	34	7
Below 9.25	1	33	8	25	29	4
All together	2	29	9	21	33	6

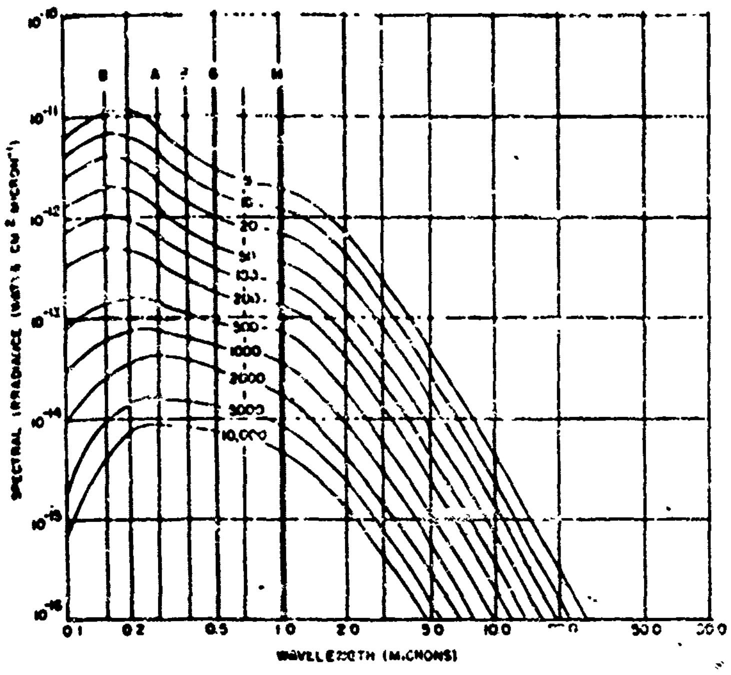


Figure 11. Minimum Spectral Irradiance of Stars for Various Population Levels, Above the Atmosphere (Reference 13)

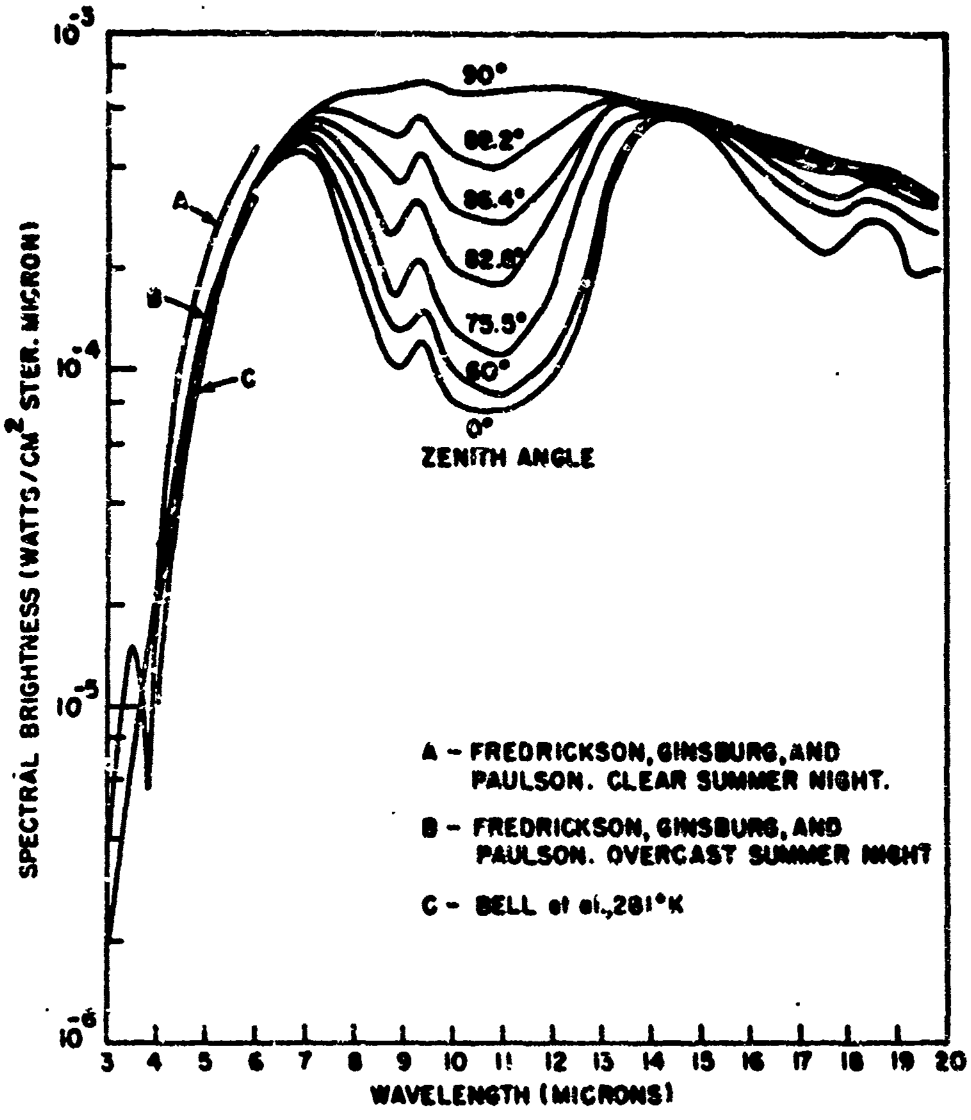


Figure 12. Spectral Radiance of Tropospheric Thermal Radiation at the Surface (Reference 14)

The nightglow at the earth's surface is shown in Figures 13 and 14 (Reference 14). Note that the ordinate is the spectral brightness at the zenith.

The objects in the scene can be a source of energy. Any object warmer than absolute zero will radiate energy as a black or gray body at any wavelength. Spectral emittance describes the capability of the body to radiate energy. Figure 15, from Reference 8, shows the spectral radiance for a blackbody as a function of temperature.

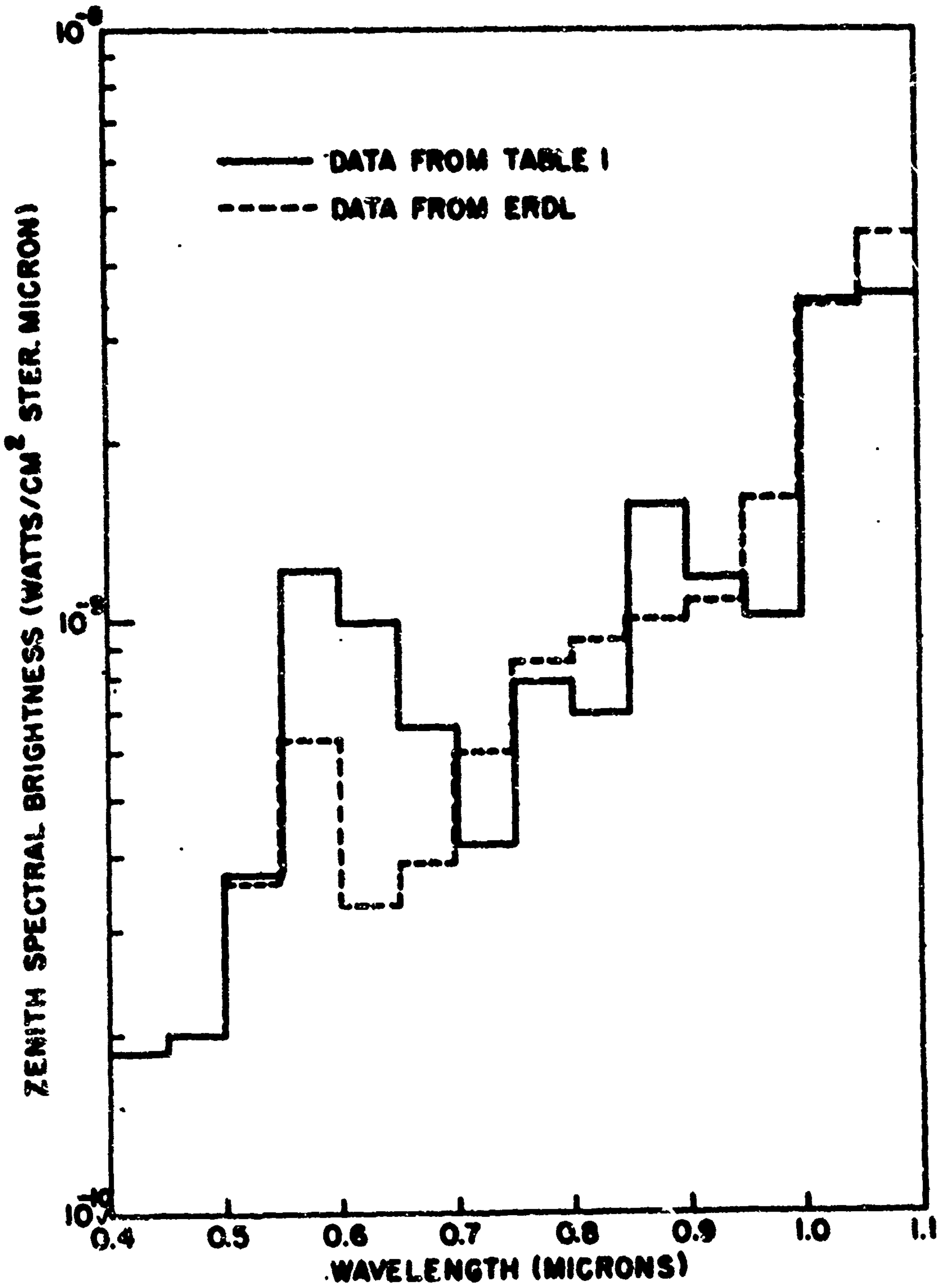


Figure 13. Spectral Radiance of Nightglow at the Zenith at the Surface for 0.4 to 1.1 μm (Reference 14)

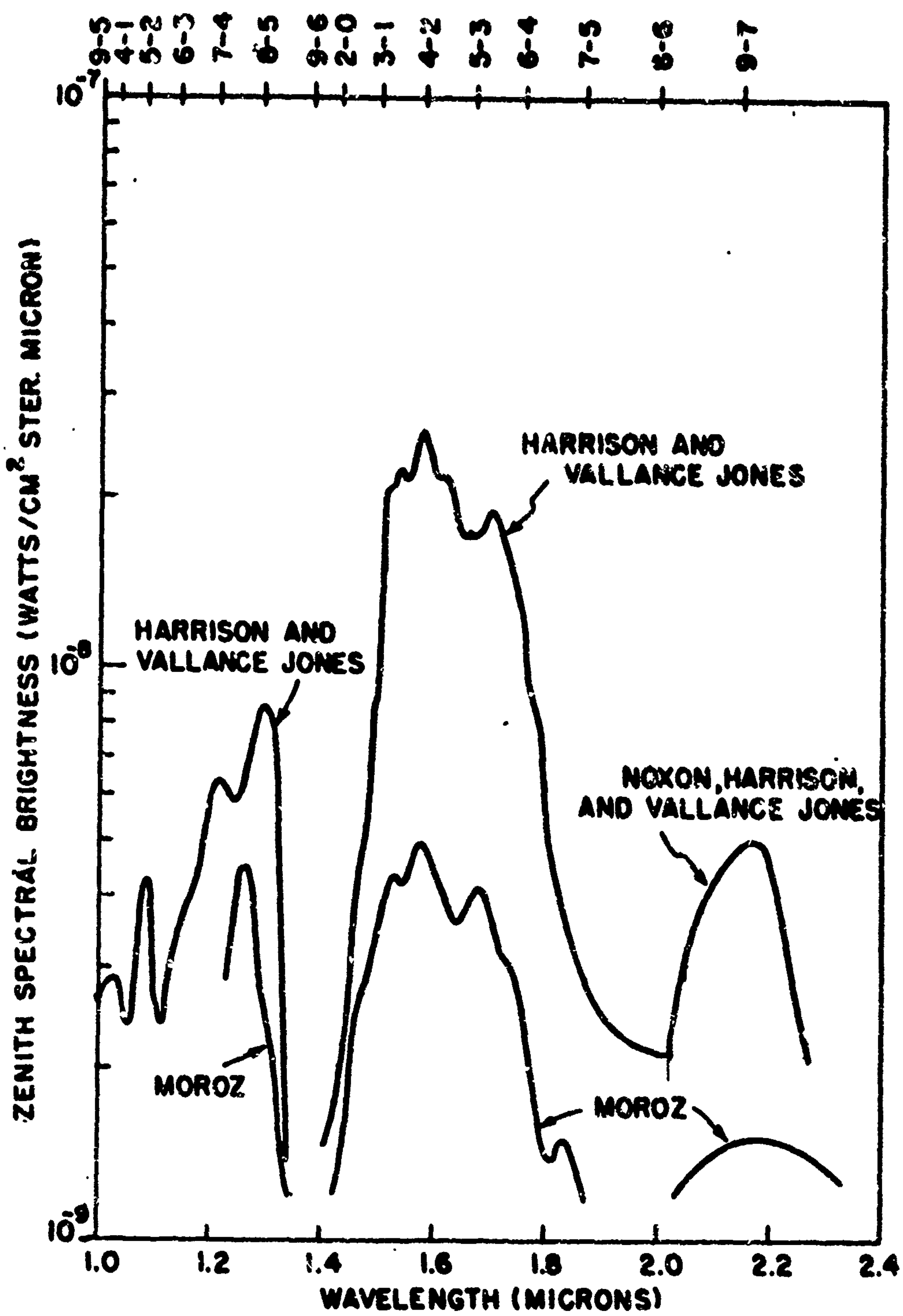


Figure 14. Spectral Radiance of Nightglow at the Zenith at the Surface for 1.1 to 2.4 μm (Reference 14)

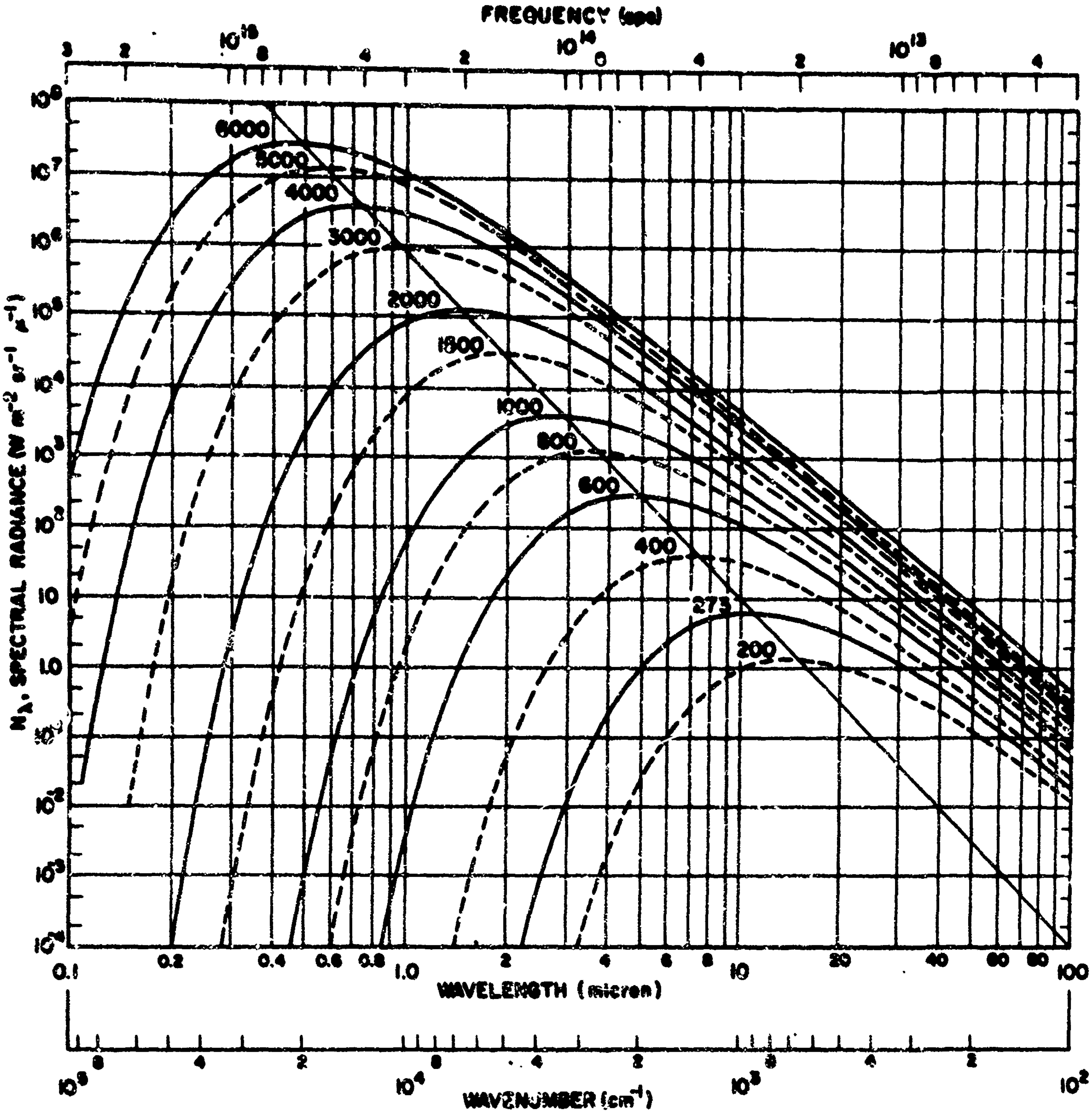


Figure 15. Spectral Radiance of a Blackbody at Typical Temperatures (Reference 8)

8.3 Atmospheric Effects

The primary causes of atmospheric attenuation from 0.2 to 14.0 μm are water vapor, carbon dioxide, ozone, and particle scattering. Hudson (Reference 15) has reproduced and extended tables by Passman and Larmore of the Rand Corporation (Reference 16). These tables permit calculating the spectral transmittance of the atmosphere at sea level with a technique to adjust for altitude and concentrations of CO_2 and H_2O. Ozone absorption at the 9.4 to 9.8 μm band is calculated by using the data on p. 159 of Reference 15. Ozone absorption at shorter wavelengths is calculated by using the tables of Elterman (Reference 17). The Elterman tables also include methods to calculate the effects of particle scattering, but data is provided to calculate effects only at discrete wavelengths from 0.27 to 4.0 μm.

8.4 Scene Effects

Energy starts at its source and passes through the atmosphere being selectively spectrally attenuated. It illuminates the scene where it is spectrally reflected. Energy generated within the scene is spectrally emitted.

8.4.1 Reflectance

Reflectance of materials can vary from 0 to 1, depending upon the proportion of incident energy which is reflected. For any material, the reflectance will vary significantly with wavelength from 0.2 to 14.0 μm. In general, no material has the same reflectance over this range of wavelengths. Reflectance changes with the angles of the incident light and the observer's sensor. Born and Wolf (Reference 18, p. 182) define the conditions necessary for isotropic radiation. If a plane surface is an isotropic radiator, it is said to be lambertian, or diffuse. Very few measurements of the angular effects exist; therefore, diffuse assumptions are frequently made.

8.4.2 Emittance

Most data are first measured as spectral reflectance and are converted to emittance by assuming opacity. For an opaque body ($\tau = 0$), we have

$$\varepsilon = 1 - \rho \tag{13}$$

This formula was used to calculate the data appearing in Reference 19. Emittance is important only beyond about 2 μm because normal objects are at ambient temperature and blackbody radiation below 2 μm at ambient temperature is less than other sources of reflected energy.

9. Radiation Calculation Techniques

Recall that the goal is to determine the factors of detection, recognition,

and identification. Basically, the sequence begins by determining the boundaries of the scene viewed by the sensor. Next the spectral irradiance entering the aperture from within each boundary defines the power entering the sensing transducer when one resolution element is focused (or scanned) on the material.

To calculate this radiation as a function of wavelength requires first determining the incident energy illuminating the scene. The data presented later in this report will define the incident energy from nightglow, starlight, the troposphere, and the moon. This energy is summed appropriately by considering the angle of the illuminated surface (note that the data is presented for vertical and horizontal surfaces). Note that the moon may not be present, or its elevation angle may vary during the observation period. Next this input energy is convolved with the spectral reflectance for each surface material to define the energy reflected toward the sensor, considering whether the surface is lambertian or not.

Each scene constituent is also considered as a blackbody source at its temperature. Radiance is multiplied by spectral emittance to determine emitted energy. Reflected energy is added to emitted energy to determine all energy leaving the scene. This energy is selectively spectrally attenuated between the scene and the sensor by the atmosphere. Finally, the attenuated values represent the energy entering the sensor aperture.

9.1 Atmospheric Transmission

The spectral transmission of the atmosphere is affected by scattering particles, ozone, water vapor, and carbon dioxide. Each of these factors varies with altitude. Data for horizontal transmission at sea level have been measured by Yates and Taylor (see Reference 20). For like data at elevated angles, the tabular data of Passman and Larmore (Reference 16) are used, as extended in Hudson (Reference 15), with the Elterman technique (Reference 17) added.

9.1.1 Horizontal Sea Level Transmission

The Yates and Taylor data have been digitized and interpolated. Curves of atmospheric transmission at sea level versus range from sensor to target are presented in Figures 16 through 29. The data for these curves were measured at ranges of 5.5 km and 16.25 km, and the intermediate values were calculated by using interpolation. Because of their bulk, these figures and all other computer-generated curves (Calcomp plots) appear after the text of the report proper.

These curves were computed and plotted for selected wavelengths on the assumption that the transmission loss at a given range is due to the attenuation phenomenon following the pattern of

$$\tau_\lambda = e^{-\ell\alpha(\lambda)} \qquad (15)$$

where τ is the transmission over a range ℓ with an attenuation coefficient $a(\lambda)$ depending on a wavelength λ. With this assumption, the extrapolation of the test data on range was performed by defining the extinction coefficient as

$$\alpha(\lambda) = \frac{\mathrm{Log}_e(\tau_\lambda)}{-\ell} \tag{16}$$

These extinction coefficients were generated for each of the wavelengths used to define the spectral curve and then used with Equation (15) at the appropriate ranges to interpolate other curves.

The interpolation of the 5.5 km and 16.25 km test data yields different results when one curve is used to predict the transmission at the range of the other curve due to the differences in temperature and the quantity of precipitable water in the optical path. The one advantage of the Yates and Taylor data as a prediction for sea level transmission is its inclusion of all attenuation factors, even though they may not be separable or individually predictable.

The 5.5 km test data was measured on 19 April 1956 at 38°F, 66% relative humidity, and 2.2 cm water in the path with a reference point of 40% transmission at 0.55 µm. The 16.25 km data was measured on the same day with 53°F, 41% relative humidity, 6.5 to 6.9 cm water in the path, and a 29% transmission at 0.55 µm as reference. The tests were conducted over the Chesapeake Bay at the Chesapeake Bay Annex of the U.S. Naval Research Laboratories.

The techniques described by Hudson (Reference 15) and Elterman (Reference 17) could also be used to generate similar curves. Such combined curves may be preferred since the Yates and Taylor measurements represent only one distinct set of conditions.

9.1.2 Elevated Line-of-Sight Transmission to Top of Atmosphere

The calculation of the energy irradiating the scene required knowing the atmospheric transmission from sea level to the top of the atmosphere for 10 zenith angles, see Section 9.2. After each factor was calculated separately, the overall transmission was evaluated as

$$\tau_\lambda = \tau_{\lambda\,\mathrm{scattering}} \cdot \tau_{\lambda H_2O} \cdot \tau_{\lambda CO_2} \cdot \tau_{\lambda O_3} \tag{17}$$

9.1.2.1 Scattering Effects

Elterman (Reference 17) defined a particle concentration which, reportedly, matches the US Standard Atmosphere for typical conditions (25 km

visible range). This reference contains a set of tables which permit determining the transmission of the atmosphere. The Rayleigh, Mie, and ozone effects from 0.27 to 4.0 μm are treated in this reference. Except for one change, the techniques of Elterman were used to calculate the scattering to the top of the atmosphere. Elterman's equation for transmission at an angle is

$$\tau_{o-h} = e^{-\tau_{ext}(n)\sec\theta} \tag{18}$$

where θ is the zenith angle. This implies a flat earth. The ratios of distance traveled to 50 km (Elterman's maximum height) for a curved earth were calculated in this study for the angles listed in Table 4.

TABLE 4

Elevation Angle Versus Ratio of Line-of-Sight Distance Traveled to the Top of a Curved Earth with a 50 km Atmosphere from the Surface

Angle	Distance Ratio	Angle	Distance Ratio
0°	1.0	80°	5.176
20°	1.064	85°	8.367
40°	1.302	88°	12.155
60°	1.977	90°	15.995
70°	2.843		

After these data were plotted, values for the ten angles representing the ten sky segments were read graphically. The ten values were used to replace the sec θ term of Equation (18). Results are plotted as Figure 30. To extend these curves, the values for wavelengths of 1.06, 2.17, and 4.0 μm were graphed on a semilog plot, as shown in Figure 31. Since these plots made reasonably straight lines in a logical pattern, they were extrapolated to 14.0 μm. Then after the data were plotted on linear scale graphs as τ versus λ, the curves were digitized. The ten curves of τ versus λ for each zenith angle are presented in Figures 32 through 41.

9.1.2.2 Ozone Effects

Elterman's tables include ozone effects below 4.0 μm. However, the above extrapolation of his data fails to include the ozone absorption at longer wavelengths. To include this absorption, the curve for ozone absorption shown in Figure 9 was scaled by the amplitudes given by Hudson (Reference 15, p. 128) for the 4.6 μm absorption peak for 4.03 atm-cm of ozone, which is the total amount in the US Standard Atmosphere. For zenith angles greater than zero, the amount of ozone in the path increases for a curved earth, as shown in Figure 42. The calculated ozone transmission effects for the ten sky segments are plotted in Figures 43 through 52.

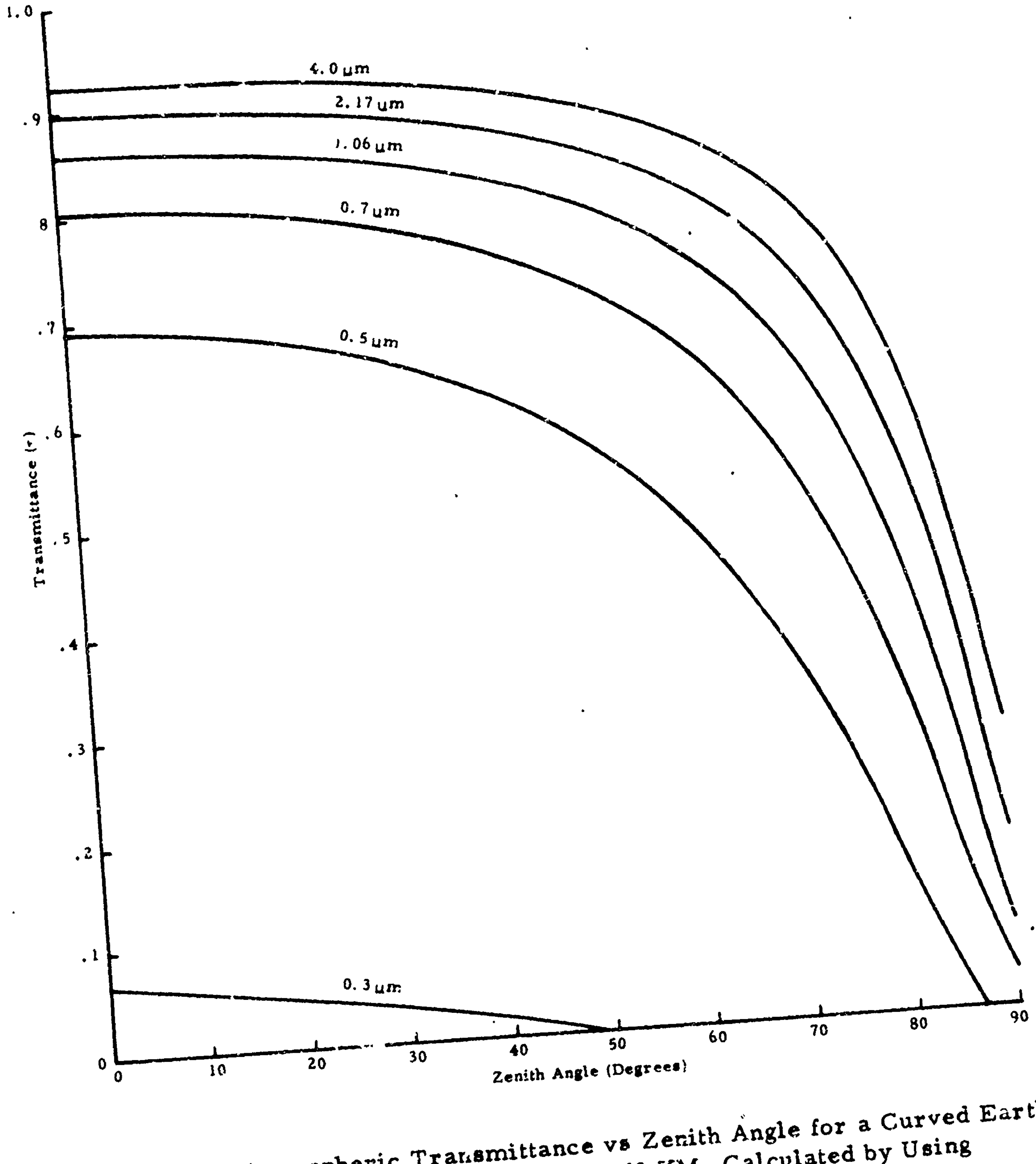


Figure 30. Atmospheric Transmittance vs Zenith Angle for a Curved Earth, for the Entire Atmosphere to 50 KM, Calculated by Using Elterman Tables

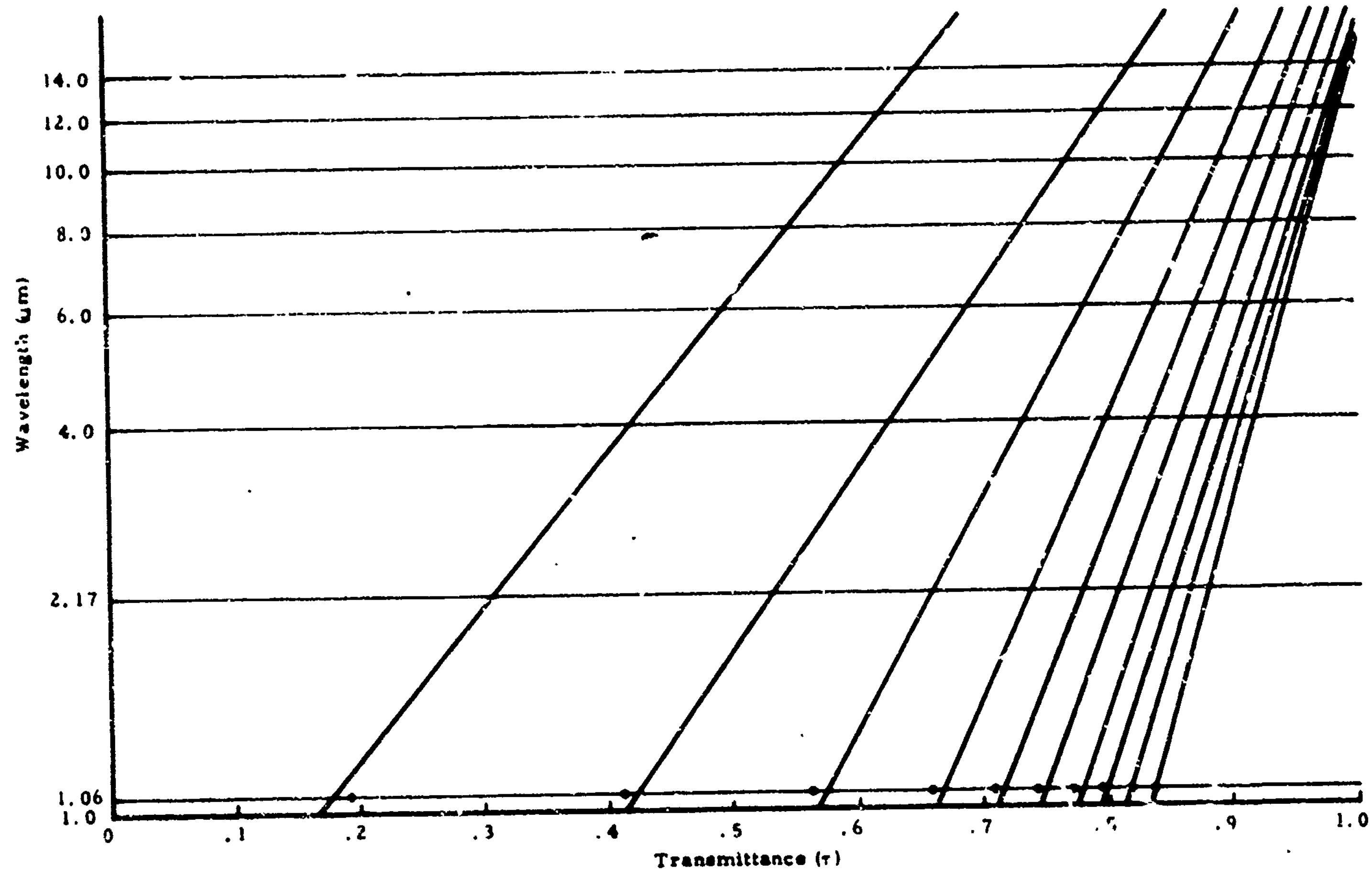


Figure 31. Plot to Permit Extrapolation of Elterman Transmittance

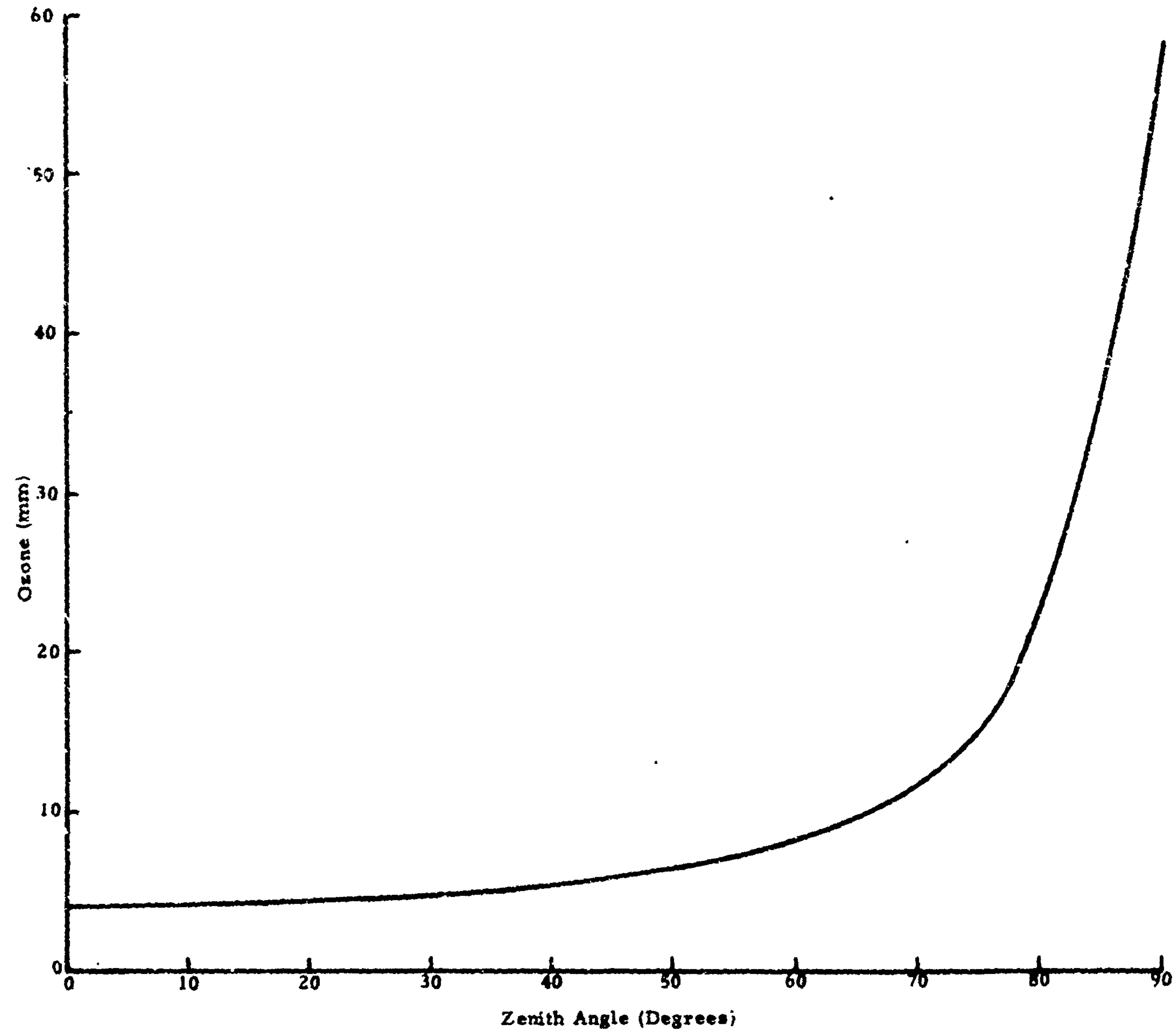


Figure 42. U. Standard Atmosphere, Ozone vs Zenith Angle for a Curved Earth

9.1.2.3 Water Vapor Effects

The altitude corrections of Hudson (Reference 15) were used to correct the water vapor contents of the US Standard Atmosphere, see p. 3-37 of the Handbook of Geophysics (Reference 8). This water vapor content is plotted in Figure 53. Again a curved earth calculation was used to adjust for the water vapor that a ray passes through at various zenith angles. The transmission effects due to water vapor are plotted in Figures 54 through 63.

9.1.2.4 Carbon Dioxide Effects

Hudson's altitude corrections were also applied to the Passman and Larmore tables for the CO_2 transmission effects. The equivalent path length of CO_2 for curved-earth zenith angles is plotted in Figure 64. The carbon dioxide transmission effects for the ten sky segments are plotted in Figures 65 through 74.

9.1.3 US Standard Atmosphere Transmission vs Elevation Angle

The above curves for the four factors affecting transmission were combined to calculate transmission versus zenith angle by using the equation

$$\tau_{atmos} = \tau_{scattering} \times \tau_{H_2O} \times \tau_{CO_2} \times \tau_{O_3} \qquad (19)$$

For ten sky segments, the spectral transmission is shown in Figures 75 through 84.

9.2 Energy Illuminating the Scene

The entire sky, across all zenith angles, can be a source of energy caused by stars, nightglow, and tropospheric thermal effects. To make a reasonably short approximate calculation of the energy effects, the sky was considered to be a hemisphere above a flat horizontal surface. Zenith angles for every one-tenth of the sky were calculated by using the methods of p. 17 in Reference 21. To define every one-tenth of the sky, the selected angles from the zenith were 25.9°, 36.8°, 45.6°, 53.1°, 60.0°, 66.4°, 72.5°, 78.5°, 84.3°, and 90°. To calculate the average attenuation due to each effect, a zenith angle representing the center of area of each of these areas was used for each 0.05 increment of the sky. These angles were 18.1°, 31.7°, 41.4°, 49.5°, 56.6°, 63.2°, 69.5°, 75.5°, 81.4°, and 87.2°. At each of these angles, the radiance of one-tenth of the sky was calculated at the scene for flat horizontal and vertical surfaces. Note that a vertical surface is illuminated by only one-half of the sky.

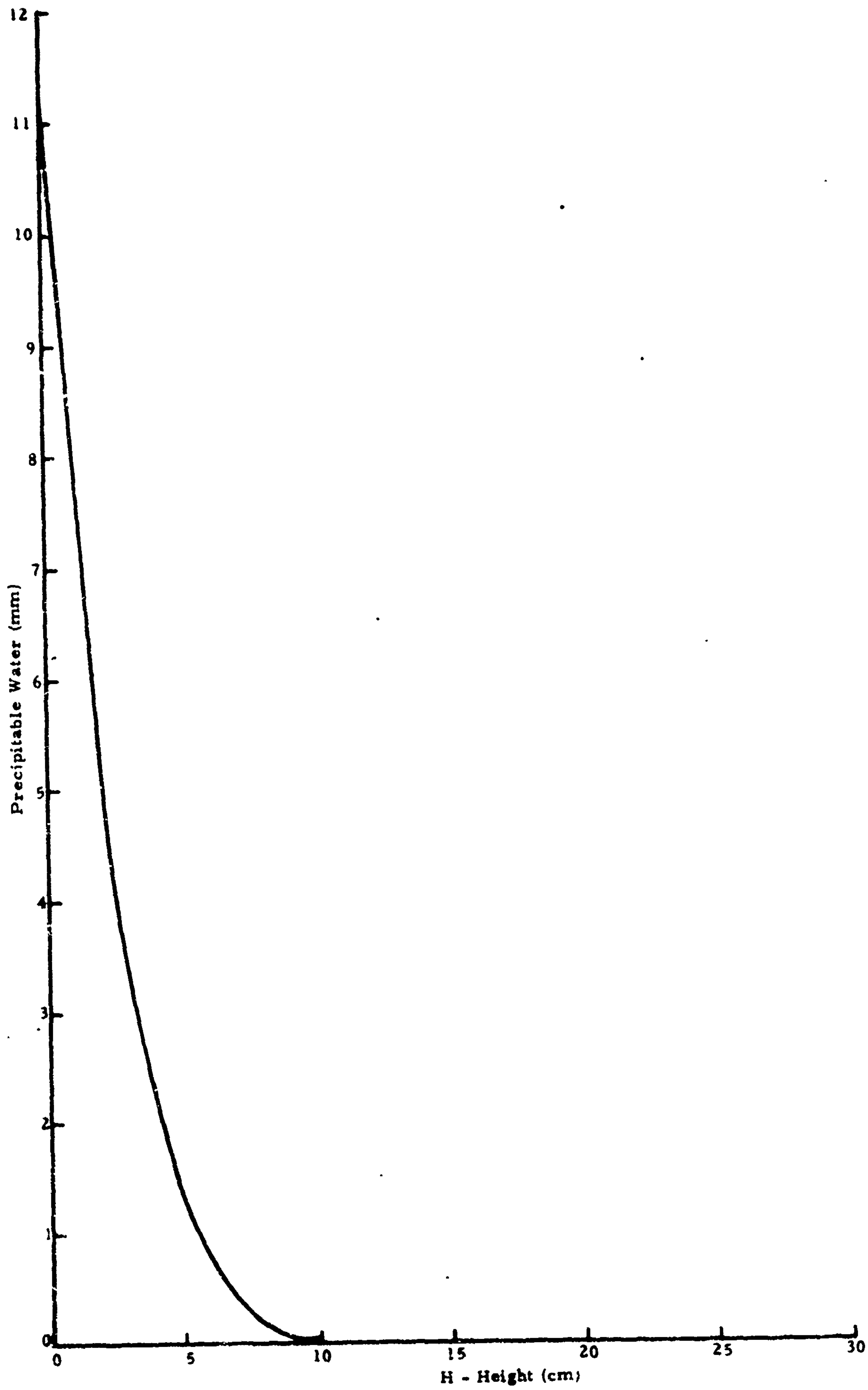


Figure 53. Precipitable Water in 2 KM Vertical Band Above Altitude H

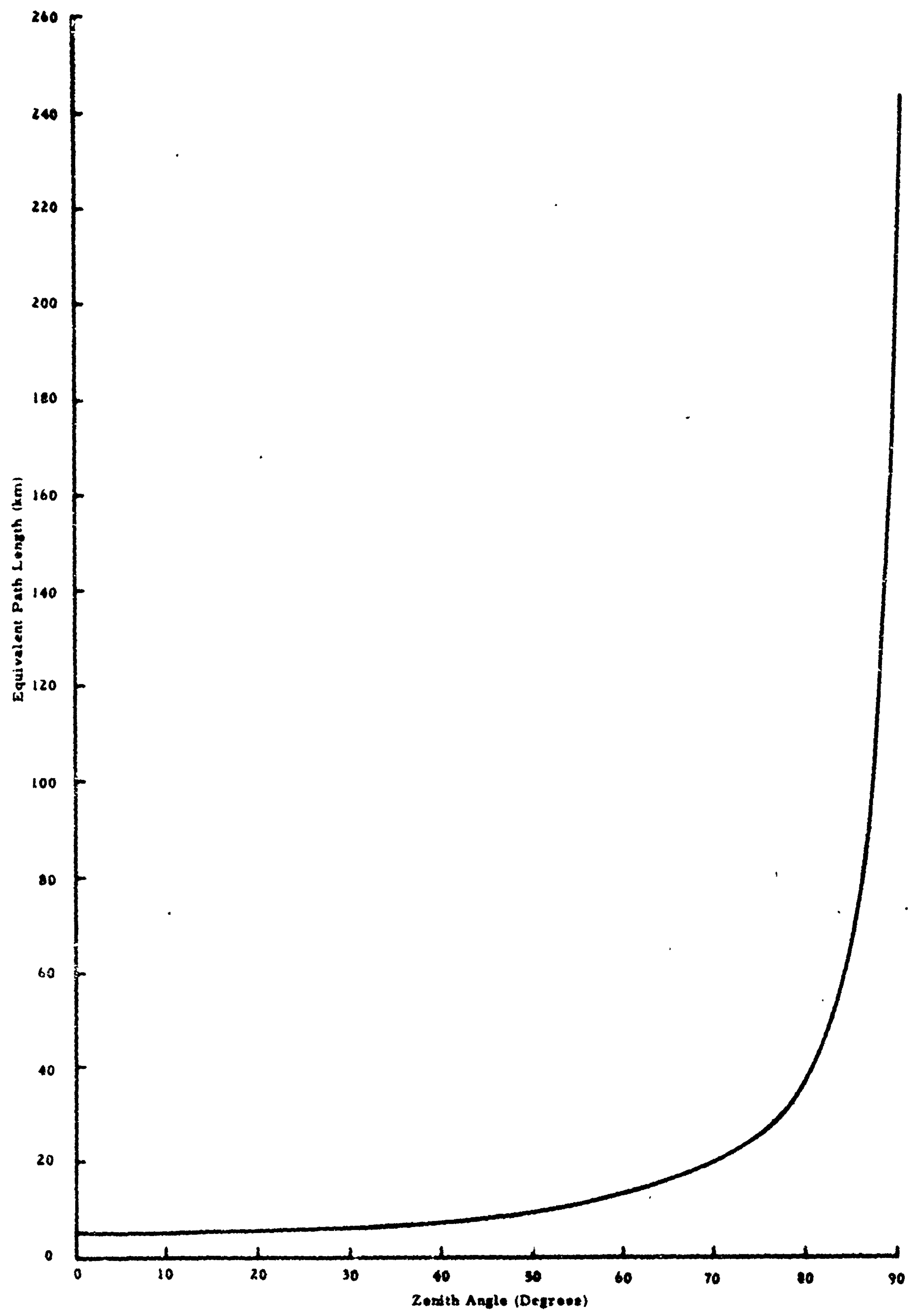


Figure 64. US Standard Atmosphere, Equivalent Path Length of Carbon Dioxide vs Zenith Angle for a Curved Earth

9.2.1 Starlight

The distribution of stars by spectral class, as shown in Table 3, was used to generate the spectral characteristics of the entire sky, considering that their equivalent irradiance is stated to be 35.8 stars of zero magnitude per steradian (assuming uniform distribution), see p. 33 of Reference 11. Multiplying 35.8 by 0.62832 sr/0.1 sky yields the spectral irradiance above the atmosphere for each one-tenth of the sky. Also the relative occurrence of each spectral class is considered. See Figure 85 for the spectral stellar irradiance for 0.1 of the sky above the atmosphere. Next the atmospheric transmission was considered for each one-tenth of the sky. Finally, the data was summed up for the total energy reaching a horizontal and vertical surface. The resultant thirty-two curves are presented in Figures 86 through 117. Of these figures, the first ten represent the starlight at the scene for each one-tenth of the sky; the second ten represent the starlight energy illuminating a horizontal surface for each one-tenth of the sky; and the third set of ten represent the starlight illumination of a flat vertical surface for each one-tenth of the sky. The thirty-first figure represents the total energy illuminating a horizontal surface, and the thirty-second represents the total energy at a vertical surface. The first 30 component curves are presented to permit the reader's calculating other situations as needed.

9.2.2 Nightglow

Reference 22 describes the constituents causing nightglow. To define the nightglow requires basically the conversion of energy from one form to another in an earth-concentric volume between the altitudes of 80 and 120 km. Accordingly, the volume for a curved earth band between these two altitudes was calculated for each one-tenth of the sky. Table 5 presents the results.

TABLE 5

Volume Between 80 and 120 km Altitude Boundaries for a Curved Earth

Sky Segment	Volume (km^3)	Sky Segment	Volume (km^3)
1	294,894	6	2,490,109
2	401,560	7	4,870,881
3	591,727	8	11,473,274
4	877,921	9	32,333,566
5	1,429,150	10	106,197,322

Figures 13 and 14 represent the spectral radiance at the earth's surface caused by nightglow at the zenith. After this radiance was scaled to the 0.1 sky elements, the volume effect was calculated directly for each segment (actually twice the volume was calculated to give twice the radiance).

These figures were attenuated by the atmosphere, and calculations were made for horizontal and vertical surfaces. The resultant 32 curves, similar to those for starlight, appear in Figures 118 through 149.

9.2.3 Tropospheric Thermal Energy

Figure 12 illustrates some measured spectral radiance caused by tropospheric thermal energy radiation. Bell, Eisner, Young, and Oetjen (see Reference 23) indicate that this effect is related to the ground ambient temperature. To calculate this effect, the emittance of the sky was estimated as

$$\epsilon = 1 - \tau - \rho \tag{20}$$

where

$$\tau = \tau_{H_2O} \cdot \tau_{CO_2} \cdot \tau_{O_3} \cdot \tau_{scattering} \tag{21}$$

and

$$\rho = 1 - \tau_{scattering} \tag{22}$$

This emittance was then multiplied by the blackbody radiation at the ambient temperature of 68°F. The resultant 32 curves, again similar to those for the preceding two sets, are presented in Figures 150 through 181.

9.2.4 Moonlight

The full moon can be a significant energy source if the moon is fairly high above the horizon. However, there are few times and places where this occurs. Moreover, the moon's reflected sunlight diminishes during the lunar month as the moon phase changes. Accordingly, the data of Figure 10 were used to calculate spectral irradiance for the full moon, as attenuated by the atmosphere, for each of the ten angles listed in Section 9.2. Reflected plus emitted irradiance is shown in Figure 182. With appropriate scaling for horizontal or vertical surface illumination, Figures 183 through 212 present the curves for these ten angles. Since the moon is a point source, summation curves are not appropriate. Partial moon radiation can be scaled from these data.

9.2.5 Other Sources

Other sources of illumination, such as aurorae, zodiacal light, and noctilucent clouds are present at certain locations. However, these sources were not included in this report because they do not provide reliable illumination at the temperate regions of the earth. The night sensing literature implies that the energy sources enumerated above constitute the major and significant sources of illumination.

10. Scene Constituents

The number of possible scenes viewed by a remote sensing device is nearly limitless; each scene, however, has in common basic characteristics, including target and background constituents.

10.1 Targets

The analysis of the target part of each scene must include the operational mode of the remote sensing device, that is, its use in an air-to-surface, surface-to-air, or surface-to-surface configuration. The targets can be broken down into three basic types: airborne vehicles, sea surface vessels, and fixed and mobile shore targets.

10.1.1 Surface Ships

Surface vessels in this report include all the known military naval vessels, both ships and boats, under 120 feet in length. Included in this coverage are the vessel types of more than 100 countires, including such categories as fast patrol boats, torpedo/missile boats, riverine patrol craft, minelayers, minesweepers, landing craft, diving tenders, military harbor tugs, some SEA paramilitary vessels such as South Vietnam fishing vessels converted to shore patrol craft, and some miscellaneous craft. The naval vessels include those of both the regular navy and the coast guard, or the equivalent organization, in the respective countries. To classify the smaller vessels of some countries is difficult since some such vessels have been built by one country and then altered by another to serve a different function. For example, the Cuban Navy converted a U.S. Higgins motor torpedo boat to an air-sea rescue vessel by modifying the above-deck construction. The problem in classification, therefore, lies in choosing between the using country's description of the vessel and its intended mission functions on the one hand, and the original intended use by the country which designed and built the equipment on the other hand. Numerous other examples could be cited for vessels that are used in any of the categories listed above.

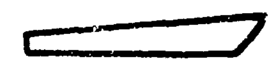
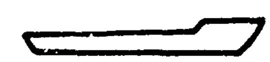
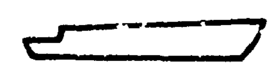
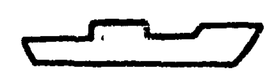
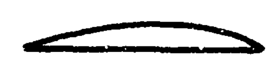
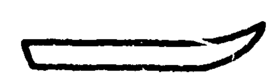
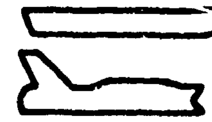
10.1.1.1 Vessels by Nationality and Dimension

Table 6, Naval and Merchant Strengths, lists the different types of ships, regardless of size and shape, for the 55 countries with the largest fleets. This table is included solely to permit comparing the vessel types by country with those vessels under 120 feet in length as listed in later tables. Figure 213 shows the hull shapes (side profiles) for fourteen hull types, including one unknown to represent hulls whose shapes could not be determined by photos or drawings. These basic hull types were the result of analyzing the 7320 vessels, 120 feet or less in length, making up the world's naval vessels. Hull type No. 2 (unknown shape) is included only to show that there are 2255 vessels in addition to the 5065 vessels whose hull shapes are known.

TABLE 6

Naval and Merchant Strengths

	Merchant Ships	Large Aircraft Carriers	Light Aircraft Carriers	Escort Carriers, Helicopter Carriers, Commando Carriers	Command Ships, Communications Ships, Amphibious Force Flag Ships	Nuclear Powered Submarines	Conventionally Powered Submarines	Cruisers	Leaders, Large Destroyers, Frigates (DLG)	Destroyers	Destroyer Escorts, Frigates, Escorts (and APD)	Corvettes (including PCF)	Patrol Vessels, Submarine Chasers (PC)	Missile Boats, Torpedo Boats, Motor Gunboats, Fast Patrol Boats	Fleet Mine-layers, Fast Mine-layers, Mine Support Ships	Coastal Mine-layers	Ocean Mine-sweepers, Fleet Mine-sweepers	Coastal Mine-sweepers, Mine Hunters	Inshore Mine-sweepers, Mine-sweeping Boats	Motor Launches, Motor Patrol Craft, River Gun-boats	Landing Ships	Landing Craft	Boom Defence Vessels, Net-layers	Survey Ships	Depot Ships, Repair Ships, Maintenance Ships	Transports	Supply Ships	Oilers	Training Ships	Tugs	Miscellaneous	Total
Argentina	318		1				2	3		9	3	3	8	1			4	6				5		3		5		8	2	19	2	394
Australia	292		1	1			2		3	7	5							6	2	8			1	2				1		3	10	344
Belgium	213											2						22	16						3					1	16	207
Brazil	421		1				2	2		11	5	10						4						6	2	4		9	1	2	2	400
Bulgaria	50						2				2		8	8			2	4	22			10							1	1	2	112
Burma											1	2	5	5			1			34		8				1					2	59
Canada	1,132		1				4				23							6		3			5	6	3		5	2		27	70	1,205
Ceylon											1									9										1	1	12
Chile	111						2	2		4	1	2	2	4							3	3		1		2		1	1	12	3	154
China	216						33			4	15		22	290			21	6		22	44	26	6	2	1		8	5		11	375	1,107
Columbia	37									3	2									22				1		6		3		13	4	91
Cuba	53										4	2	14	42						27										1	6	149
Denmark	901						4				6	4		16	4	4		8	4	13					3			2			7	976
Dominican R.										2	3	5	7							7	1	2						2		5	2	36
Ecuador											3	2								8	2									2	2	19
Egypt	112						13			6	3	3		62			6		2			18				1					2	220
Finland	411										3	2	4	15		2			5	13						4				3	10	477
France	1,532		3	1			19	2	2	18	28		14				15	71	15	13	9	10	12	9	10	10	16	19	4	20	50	1,893
Germany (E)											4		24	72			20		24	60		18		3				3	2	7	24	261
Germany (W)	2,504						12			9	21	6		40	2			24	51	24	4	22		8	16		6	10	3	18	40	2,820
Greece	1,290						3			8	4		7	8		2	5	14			16	8	1	2	2			7		14	10	1,401
India	347		1				4	2		3	14							4	2	5	1	1		4	1			3		1	10	403
Indonesia	393						12	1		7	11	3	12	64			6	15		82	8	7		2	3	4		4	2	5	5	646
Iran										1	1	5						4	2	24		3			1			2		1	2	46
Iraq													3	12						4										1	2	22
Israel	98						4			2			1	12						4		6									2	129
Italy	1,421						8	4	4	4		24	7	16			4	37	20		1	23	2	2	1	5		2	4	26	90	1,710
Japan	5,401						9			26	16		20	19		2		40	6	32	4	6			3			2	10	3	100	5,699
Korea (N)							2						18	42			10		24	15											70	181
Korea (S)	59									1	12	10	7					11	1		20				1	1	6	4		2	4	141
Malaysia	131										2			4				6	2	25				1							2	173
Mexico	86										8	21	1							8				1		1		2			1	129
Netherlands	1,809		1				6	2		12	6	12						41	16	5		7	1	3	1		3	1	3	7	20	2,036
New Zealand	146										4		1				4			12				1			1				2	171
Norway	2,732						15				5		2	47		5		10						1	2				1		9	2,829
Pakistan	128						1	1		5	2							8		6				1				2		4	3	153
Paraguay																				8											1	9
Peru	60						4	2		2	3	2						2		16	4					3		4		2	3	107
Philippines	174											6	6					2		20	6			1	1	1		1		4	5	227
Poland	304						11			3			8	25			21	4	27	36		22		1				4	2		4	356
Portugal	341						3				13	1	14				4	12		40		4		6	2			2	1		11	454
Rumania													3	12			1		30										2		30	81
South Africa	165									2	6						1	10		10			1	1				1		1	2	200
Spain	1,761			1			8	1		18	6	6	2	3	6		13	12		18	8		1	3		3		4	1	19	20	1,905
Sweden	1,167						24	1		8	8			42	1	10		18	19	24		23		12	2		1	3	2	17	17	1,382
Taiwan	117									5	13	5	23	48		1	5	8		50	45	50		2	3	6		5		5	60	430
Thailand											5		14			2	1	4		8	5	8		1		1		4	1	5	3	62
Turkey	294						10			10		9	6	8	1	6	9	13	3	30			6	2				4	1	2	5	410
United Kingdom		2	2	2		7	37	3	4	16	78		4	7	1	5		76	23	5	3	26	28	15	13		17	30		70	210	682
Uruguay	37										3		4											1				1				50
USA	3,537	35	2	21	9	85	116	36	33	346	252	9	25	10	14		94	30	43	400	150	126	4	26	70	40	125	75	2	250	940	6,003
USSR	3,674					55	325	25		100	100		300	475			160	145	45	120	124	100	18	55	50	25	20	50	20	40	900	4,932
Venezuela	81						1			3	6		12							12	4			3	1	1				2	3	129
Vietnam												6	2	14				3			10	23					1	2		14	10	85
Yugoslavia	350						4			3	2		2	100	1			4	34	18		7				2		6	1	8	30	562
Total	32,536	35	13	26	9	107	702	87	48	658	718	162	600	1514	30	36	417	600	438	1314	479	564	86	106	107	131	207	204	67	614	3215	46,223

Hull Type	Number of Vessels	Hull Shape
1	3996	
2	2255	Unknown
3	500*	
4	268	
5	134	
6	94	
7	14	
8	13	
9	12	
10	10	
11	8	
12	8	
13	7	
14	1	
Total	7320	

* Approximate (South Vietnam fishing vessels used in coastal patrol missions)

Figure 213. Number of Small Surface Vessels by Hull Shape (side profile)

Table 7 lists the number of vessels by hull shape versus length. Table 8 gives these same vessels by hull shape versus width (beam). And Table 9 lists the vessels by hull shape versus height (from waterline to top of superstructure, masts and antennas not included). The comparison of the 7320 vessels under 120 feet in length with the 13,685 naval vessels listed in Table 6 indicates that about 53.5% of the military naval vessels are 120 feet or less in length. The total approximate number of such merchant and military vessels is 46,223, as listed in Table 6. If coastal pleasure craft and fishing vessels are excluded, the odds that a sighted ship is a naval vessel under 120 feet in length is one in every 6.67 sightings. Of course, local conditions may either raise or lower these odds. Certainly the odds increase considerably if pleasure craft and fishing vessels are included. These latter craft could be used in paramilitary operations such as the smuggling of arms and supplies to insurgents in guerrilla-type warfare. Table 10 lists by hull type (see Figure 213) the number of naval vessels for 103 countries. These numbers include, but are not limited to, fast patrol boats, torpedo and missile boats, minesweepers and small minelayers, landing craft, diving tenders, and small harbor tugs. This table is included to indicate the relative number of naval vessels under 120 feet in length among the given countries. The average dimensions for naval vessels under 120 feet in length are as follows: length, 50 to 90 feet; width (beam), 16 to 22 feet; and height (from waterline to top of superstructure, not including masts or antennas), 14 to 16 feet.

TABLE 7

Hull Type Versus Length

Hull Type	Length (in feet) 20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-120	Unk
1	1	570	72	883	125	636	1218	147	184	159	1
2	18	43	164	104	118	137	56	91	72	110	1342
3				500							
4				48		45	18	10	142	5	
5						14				120	
6			4			16		32	10	32	
7					13			1			
8										13	
9								2		10	
10									10		
11			3	1		2				1	1
12							6	1	1		
13		6	1								
14										1	

TABLE 8

Hull Type Versus Beam

Hull Type	Width (in feet) 6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30	30-32	32-34	Unk
1		1	598	837	108	714	392	1037	2	74	3		1		229
2															2255
3						500									
4					49	157	3	1	4						54
5							14							119	1
6			11		26	14	24	2	10		5				2
7					13		1								
8								13							
9							1	2	1	8					
10									10						
11	4	3													1
12											6				2
13									7						
14									1						

TABLE 9

Hull Type Versus Height (Waterline to Top of Highest Structure on Deck not Including Tubular Masts or Antennae)

Hull Type	Heighth (in feet) 4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30	Unk
1	272	338	166	566	416	964	231	268	62	2	4	0	0	707
2														2255
3		500												
4					69	2	120	1	4	15				57
5							14		106	13				1
6				8	[illegible]	10	13	11		4		4		19
7							14							
8								13						
9									2	10				
10													10	
11	1	1	4			1								1
12							1	6						1
13							6							1
14								1						

TABLE 10

Number of Naval Vessels Under 120 Feet in Length by Hull Class Per Country

	Hull Class														
Country	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Albania	16	12		6											34
Algeria	12	27													39
Argentina	22	6													28
Australia	26	9													35
Belgium	16	21				1									38
Brazil	2														2
Brunei	1														1
Bulgaria	36	≈50													≈86
Burma	35			4		10									49
Cambodia	52	13			6										71
Cameroon	4														4
Canada	13	69					13								95
Ceylon	22	1				4									27
Chile	8	3			3										14
China, Nat.	85	44			30										159
China, Peoples'	278	408			8										694
Columbia	8	28				3									39
Congo, Republic		11													11
Costa Rica		3													3
Cuba	58	12				4									74
Cyprus	6	10													16
Denmark	23	28				14			2						67
Dominican Republic	7	6			2										15
Ecuador	8	1													9
Egypt	50	16		3											69
Eire		4													4
El Salvador	2														2
Ethopia	11	4													15
Finland	28	20		1									6		55
France	21	96													117
Gaboon	1	1													2
Germany - Fed.	28	67				13					1				109
Germany - Peoples'	60			71											131
Ghana	8														8
Great Britain	56	118			15	4							1	1	195
Greece	49	19			8										76
Guatemala		5													5
Guinea	14														14
Guyana		4													4
Haiti	4	2													6
Honduras		3													3
Hungary		23													23
Iceland	1					1									2
India	9	18													27
Indonesia	81	23		1											105
Iran	9	9		11											29
Iraq	12	22													34
Israel	14					3									17
Italy	71	80				4									155
Ivory Coast	4														4
Jamaica	3														[illegible]
Japan	167	215			6	2		13					1		404
Kenya	4														4
Korea-North	43	52		12											107
Korea-South															---

TABLE 10 (concluded)

Number of Naval Vessels Under 120 Feet in Length by Hull Class Per Country

Country	Hull Class (Cont'd) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Kuwait						8									8
Laos		4+													4+
Lebanon	3	1			1										5
Liberia	4	+													4+
Libya	5	9													14
Malagasy															---
Malaysia	31	2					1								34
Maruetania	2														2
Mexico	2	6													8
Morocco	1														1
Netherlands	22	32													54
New Zealand	12	2													14
Nicaragua		7+													7+
Nigeria	7	2													9
Norway	47	7													54
Pakistan	6	3													9
Panama		5													5
Paraguay		6													6
Peru	9	4													13
Philippines	18	25													43
Poland	50	48													98
Portugal	24	64													88
Rumania	10	19+			22										51
Saudia Arabia	1	32													33
Senegal	3														3
Sierra Leone		1													1
Singapore	7														7
Somalia	12	2													14
South Africa	10	1													11
South Arabia	3														3
Spain	1	28				3					4				36
Sudan	4														4
Sweden	100	72				1			10		1				184
Syria	24	6+													30+
Tanzania						4									4
Thailand	11	7			6										24
Togo		4													4
Trinidad & Tabago	2	2													4
Tunisia	12														12
Turkey	32			4											36
Uruguay		1													1
U.S.A.	1396+	122		62	42	1				10	2		6		1641+
U.S.S.R.	350+	25+			70										445+
Venezuela	8	4													12
Vietnam-North	39	48													87
Vietnam-South	129	91	500		7										727
Yugoslavia	111+	+		1		14						1			127+
Zambia															---
	3996	2255	500	268	134	94	14	13	12	10	8	8	7	1	7320+

Note: The "+" after some figures denotes additional, but unknown, numbers; the U.S.S.R. figures with this symbol may exceed 500.

10.1.1.2 Ship Surface Materials and Coatings

Three basic materials are used in the construction of naval vessels: steel, aluminum, and wood. Coatings for these basic materials may vary from country to country, but generally the final coat is a shade of gray paint. However, some landing craft may be painted an olive drab with various spots of several shades of green. Naval vessels are usually colored gray since it offers the lowest overall contrast to the sea/air background in the visible part of the spectrum in day/night observations. Figure 214 illustrates the spectral reflectance of a typical military naval paint in the spectral range from 0.3 to 14μm. Based upon a 0.3- to 2-μm curve in the Air Force Target Signatures Library, the curve in Figure 214 was extrapolated from 2 to 14μm according to information given by Mel Greenberg, NSRDC (Naval Ship Research and Development Center). Spectral emittance for this paint was calculated as $1-\rho$ and is plotted in Figure 215. Actual paint samples were limited to the data found in Reference 33 which covers gray naval paints (see Figures 216 through 218) and an olive green naval paint (see Figure 219). Since by U.S. military standards, the paints including subsurface coatings are applied to at least a 2.5-mil thickness, the paints are opaque in the 0.2 to 14.0 μm region; therefore, the substratum has no reflected energy. This condition should prevail for all well-maintained naval vessels, but not necessarily for small SEA (Southeast Asia) patrol craft that are converted fishing-type vessels. For example, South Vietnam has numerous fishing vessels constructed principally of Sao (Hopea odorata), a brownish wood which turns reddish brown with age; or Sen bobo (Smorea hypochra), a yellowish wood which turns brownish when weathered under marine conditions. Neither of these two woods has been measured spectrally to our knowledge. For reference purposes only, three figures are included to represent curves for wood: Figure 220 for a weathered fir board, Figure 221 for a redwood board, and Figure 222 for a sanded oak board. Although the aging of the last two woods is not known, their higher reflectance in the 0.8 to 2.0 μm region indicates that they were much more recently cut than the fir board. If this assumption is true for the Sao and Sen bobo woods which are primarily used in South Vietnam patrol vessels and fishing boats, then the more weathered vessels would have lower reflectances out to 2.0 μm. This assumption also includes the supposition that the patrol craft are unpainted, as is the custom with the fishing vessels at that area. These fishing vessels are usually removed from the water at least once a year to drive out or kill woodworms by charring the hulls with burning bamboo. The caulking consists of ground bamboo and resin (primary), or shredded bamboo and coconut husk mixed with resin. For most vessels between 8 and 15 meters, the basic construction is a keelless, hard chine planked hull. Other constructions include the keel and rib type with round bilge and planked hull which was introduced in 1960.

10.1.1.3 Extrinsic Characteristics

Two extrinsic characteristics—exhaust and wake—are important factors in detecting surface vessels. Three types of vessels cause these

wakes. The first, which includes by the far the most vessels, is the hull-borne boat. The interaction of the wake with the wind waves will vary considerably with the speed of the vessel; hull configuration; relative direction of wind waves and swell to the direction of the vessel; and period, height, and fetch of waves and swell. The second type, which is limited to fewer than 100 vessels, is the hydrofoil boat. Although the United States vessels are primarily experimental and limited to about three, the U.S.S.R. and the People's Republic of China together pcssess approximately 75 which are used as fast patrol boats. When they are hydrofoil-borne, their wake will be due little to foil, but much more to the propelling device (either conventional screws on the struts of the hydrofoils or water-jet/propulsion motors). The last type, which is limited to fewer than 10 vessels, is the air-cushion "air boats." Restricted to coastal, river, and swamp areas where the water is relatively calm, the air boats move across the water on a cushion of air approximately 4-feet thick. They are kept aloft by a lift fan and propelled forward by an aft-mounted propeller. Although the wake of the air boat is negligible, a heavy aerosol develops which either remains stationary ith respect to the vessel or slowly moves around it because of the downward lift fan. At faster speeds (up to 60 knots), a "wake" may develop as the cushion of the vessel bumps the crest of small waves. Spectral reflectance and emittance data for "white water" for both breakers and the interface of waves and wake could not be found. The second extrinsic characteristic, exhaust, is emitted from three main type of engines: marine diesels, gas turbines, and fuel-oil-fired boilers. The marine diesel is the most common engine type for propelling these smaller vessels. Although a few vessels using this type of engine have stacks or funnels, such as the Yugoslavian "Y" type river patrol boat, most use exhaust systems installed near the waterline on the transom. Some older boats still use reciprocating gasoline engines. The second type of engine, the gas turbine, is the most recent type to be installed in naval vessels. At present it is limited to newer designed craft which require faster speeds, such as fast patrol boats. Although some of these vessels have funnels, most have two or three exhaust ports in the transom. The last type, the fuel-fired boiler/steam turbine type, is not common among the smaller craft. Funnels are used in vessels with this engine type. Since the extrinsic characteristics accompanying each system differ, the detection must consider the type of engine, type of fuel, speed of vessel, and speed and direction of the wind in relation to the direction of the craft. During this study no spectral data was found describing exhausts from burnt hydrocarbons, nor the density of the exhausts and the rate of exhaust dispersion into the surrounding atmosphere.

10.1.1.4 Target Temperatures

Although no temperature data was available for small surface vessels, such data was found for a destroyer (see References 34 and 35). The vessel temperatures in this data were related to the ambient air temperature. Although the absolute temperatures varied as both a function of time and

vessel location, the formulas in the above references appear to be representative for different parts of the vessel throughout the night. This destroyer was powered by four boilers driving two turbines which in turn mechanically drove two screws. These turbines developed 60,000 horsepower. An average fast patrol boat has either one or two diesel engines or one or two gas turbines that develop between 4800 and 10,500 horsepower. Because vessels with diesels and gas turbines do not require boilers, the hull temperature of such vessels from midship to the transom along the vessel sides should nearly equal those derived from the formula given in Reference 39 for the superstructure temperature. Transom temperatures are not available, but should depend upon the type and size of the engine plus the speed of the vessel.

10.1.1.5 Sources of Variation

Among the several surface ship variations are the weathering of exposed substratum and painted external surfaces. With reference to Section 10.1.1.2, Ship Surface Materials and Coatings, the weathered wood (see Figure 220) reflected less energy than the more recently cut lumber (see Figures 221 and 222). This variation is intended only for those vessels in SEA where protective coatings are not normally used. Spectral curves for the coatings of only two types of paints have been depicted in Figures 216 through 219. NSRDC Report C-2440, dated August 1967, gives other spectral data on naval paints. Weathering of coatings with these paints will cause some spectral changes across the spectrum, particularly in the visible and near infrared regions. These changes are caused by both varying surface conditions (degree of roughness) and chemical reactions. All plots for the target materials, except water, are spectral diffused reflectance curves; however, there are no real target materials which are lambertian reflectors. Therefore, depending upon the target material, differences will occur as the viewing angle approaches the norm and as it approaches 90° from the norm. Everything else being equal, the smoother the finish, the greater the variance will be for the different viewing angles. To some extent, this effect of different viewing angles is cancelled out because the radiation from the night sky is from a hemisphere (or half a hemisphere in the case of vertical surfaces) when the moon is not present as an illumination element. That the viewing angle difference is not entirely cancelled out is due to the fact that the night sky is not radiating energy equally from that hemisphere. Another source of variation is that not all naval vessels are painted the same shade of gray. Variances will occur worldwide and probably within each country. In fact, some vessels are painted olive drab, olive green, or a combination of these colors. The reflectance curve in Figure 219 represents the only camouflage naval paint which was available for this study. However, these paints would be more likely used in landing craft and riverine patrol craft. In addition, experiments with special paints have been made to extend their usefulness into the infrared part of the spectrum so that they will "blend in" with the surrounding water; however, this is not considered very practical since the water is very nearly a specular reflector. Another method of decreasing the contrast of the vessel with its background is to cool the vessel to ambient

air or sea temperature. Techniques used in Reference 34 proved to be more effective during the daylight than during the night. Since the temperature varies little during the night, this technique would not likely be practical. Moreover, for camouflage applications, this technique would be useful in a limited spectrum range, from about 2.0 to 14.0 μm, where the radiance values are primarily from target emittance.

10.1.1.6 Ship Data Sources

10.1.1.6.1 General

Data used for the size and distribution of ships came from two basic sources: Jane's Fighting Ships, editions 1957-1958, 1961-1962, 1967-1968, and 1968-1969 (References 24 through 27) and Weyer's Warships of the World (Reference 28), 1969 edition. Both of these sources are basically in agreement, particularly for the larger naval vessels. For the smaller vessels, however, the lengths differ, normally less than a foot. One edition of Jane's lists the Russian P-4 dimensions as 82 by 16.8 by 5.5 feet, whereas another edition gives the dimensions as 82 by 20 by 6 feet. Moreover, the 1968-69 edition of Jane's gives the length as 63 feet, instead of 82 feet. These references were not intended to give detailed data about the smaller naval craft. Probably better data for both number and types of these craft is available within the intelligence organizations of the Navy, most probably in the NWIP series. In addition, information on SEA fishing vessels was gathered from the Blue Book of Coastal Vessels South Vietnam, 1967 edition, (Reference 29), the Blue Book of Coastal Vessels Thailand, 1967 edition (Reference 30), and the Green Book of Coastal Vessels Thailand, 1967 edition (Reference 31). Data for gray paint as shown in Figure 214 was taken from page 176, Night Reconnaissance Subsystem, final technical report, November 1964, Martin Marietta Corporation (AD 355 324) (Reference 32). The data on the gray and olive green naval paints were taken from Forsvarets Korskningsiad (Research on Camouflage Spectral Analysis) by the Danish Defense Research Board (AD 370 905) (Reference 33). The temperature data discussed above were extracted from two reports: The Surface Temperature and Infrared Radiance of the U.S.S. Gyatt, by NRL, 9 October 1969 (Reference 34); and The Infrared Radiant Intensity of the U.S.S. Gyatt, by NRL, 15 October 1969 (Reference 35). Data for the three woods were taken from the University of Michigan's target signature bank (Reference 36).

10.1.1.6.2 Processed Data

The gray paint curve shown in Figure 214 is the result of correcting a basic document reflectance curve from a $MgCO_3$ standard to an absolute curve from 0.3 to 2.0 μm. Then the resultant curve was extended to 14.0 μm on the basis of a telephone conversation with Mel Greenberg from NSRDC who stated that nearly all naval gray paints were no greater than 27% in the visible part of the spectrum and that after 3 or 4 μm they were relatively flat out to 14 μm. The data for the wood materials were changed from

relative reflectance curves to a MgO standard to absolute curves, but they were not extended since no other logical data could be gathered to do so. The data in Tables 7 through 10 and Figure 213 were extracted from information in Jane's and Weyer's (References 24 through 28).

10.1.1.6.3 Data Gaps

For the naval gray paints on both U.S. and foreign vessels, the spectral diffused and directional reflectance and emittance data have gaps throughout the 0.2 to 14μm region. Mel Greenberg, of NSRDC, stated that two limited-access documents on some U.S. Naval paints have been published by his organization, but this information was not available in time to acquire and incorporate into this study. In addition, if boats and/or ships that could be used as paramilitary vessels, such as some fishing craft in SEA, are considered, then spectral reflectance and emittance curves would also be needed for the woods and other materials in their construction. Numbers and types of naval craft for each country, particularly those behind the iron curtain, is somewhat lacking.

10.1.2 Aircraft

The current numerous types and sizes of naval and air force aircraft may be initially divided into five basic types of propulsion: jet, propeller, rotary wing, lighter-than-air, and glider. Aircraft can also be grouped in military and civilian categories. The military aircraft can be further categorized as follows:

(1) Bomber
(2) Fighter
(3) Reconnaissance
(4) Transport
(5) Trainer
(6) Search and Rescue
(7) Communications - Utility
(8) Special Research
(9) Target
(10) Pilotless Aircraft
(11) Guided Missiles
(12) Glider
(13) Lighter-than-air craft

This report treats of only jet fighter and bomber aircraft since they pose the greatest threat to surface vessels, although remote controlled pilotless aircraft used as "flying bombs" and launched from either land-based or sea-surfaced vehicles could also pose a similar threat. Table 11 lists the known jet fighter and bomber aircraft that are being built in various countries. This listing indicates that only four or perhaps five countries are building combat fighter aircraft: France, Great Britain, U.S.A., U.S.S.R., and possibly Sweden. These countries have sold older jet aircraft to many smaller powers, and in some cases, new aircraft have been sold or given to the smaller powers through military aid programs. For example, the USAF F-111 was to have been sold to Australia, and the MIG-21 can be found in Egypt. Whether the latter example is an instance of military aid is not certain; in any event, the MIG's are flying under the flag of the U.A.R. Most

TABLE 11

Fighter and Bomber Aircraft Currently Manufactured

Country	Aircraft Designation	Wingspan	Length	Range (mi.)	Speed
Australia	Dassault Mirage III-D	27'	~ 48'	305+	870 mph
Canada	CL-41A & G(CT-114 Tutor)	36'5.9"	32.0'	NA	480 "
Czechoslovakia	L-29 ("Maya")	33'9"	35'5-1/2"	397+	382 "
Egypt	HA-300	19'4"	40'8"	NA	NA
France	Mirage III-B	27'	50'6-1/4"	305+	870 "
	-C	"	48'5-1/2"	"	"
	-E	"	49'3-1/2"	"	"
	-R	"	50'10-1/4"	"	"
	Mirage F1	27'10-1/2"	49'2-1/2"	2050	Mach 2.2+
	Mirage G	42'8"	55'1"	4000	Mach 2.5+
	Mirage III-V	28'7-1/4"	59'1/2"	NA	NA
	Mirage IV	38'10-1/2"	77'1"	NA	Mach 2.2
	Potez 94	37'3/4"	33'6"	995	485 mph
India	HAL HF-24 Marut	29'6-1/4"	52'3/4"	NA	Mach 1.02
	HAL/HAWKER Gnat	22'2"	29'9"	500	Mach 0.98
International	Sepecat Jaguar	27'10-1/4"	50'11"	405+	840 mph
(Anglo-French)	VFW/Fiat VAK 1913	NA	NA	NA	NA
Italy	Aermacchi	34'8"	34'11-1/4"	708+	478 mph
	Fiat G91Y	29'6-1/2"	38'3-1/2"	460	Mach 0.93
Sweden	SAAB-35 Draken A	30'10"	50'4"	350	Mach 2
	B	"	"	447	Mach 1.4
	SAAB-37 Viggen	34'9-1/4"	53'5-3/4"	NA	Mach 2+
	SAAB-105 (sk 60)	31'2"	34'5"	870	447 mph
Switzerland	FFA P-16 Mk III AA-7	36'6-1/2"	48'8-3/4"	380	708 mph
	AJ-7	"	"	465	727 mph
	AR-7	"	"	627	690 mph
United Kingdom	BAC Lightning FMK 6	34'10"	55'3'	NA	NA
	Hawker Siddeley Harrier GR MR1	25'3"	46'4"	500	Mach 0.95
	" " Buccaneer S. MR 50	42'4"	63'5"	NA	NA
	" " Vulcan B. MR. 1	99'	97'1"	NA	NA
	" " " B. MR. 2	111'	99'11"	1725+	Mach 0.94
U.S.A.	Cessna A-37	35'10-1/2"	29'3-1/2"	460	507 mph
	Republic F-105 Thunderchief	34'11.2"	69'1.18'	2070	Mach 2.25
	General Dynamics F-111A	63'	66'9"	3800	Mach 2.5
	General Dynamics F-102 Convair Delta Dagger	38.1'	68.3'	950+	680 knots
	General Dynamics F-106 Convair Delta Dart	38'	70'	NA	Mach 2+
	Grumman Intruder A-6A	53'	54'7"	3225	620 mph +
	Grumman Intruder EA-6A	53'	55'3"	2995	NA
	Grumman Intruder EA-6B	53'	59'5"	NA	NA
	Lockheed F-101 Voodoo	39.7'	67.4'	1000+	870 kts
	Lockheed F-104 Starfighter	21'11"	54'9"	745	Mach 2.2
	Lockheed YF-12A	55'7"	107'5"	NA	NA
	Ling-Temco-Vought Crusader F-8A/B	35'8"	54'3"	600	1000 mph +
	Ling-Temco Vought Crusader F-8C/D	35'2"	54'3"	NA	Mach 2 -
	Ling-Temco-Vought Crusader F-8E	35'2"	54'6"	NA	Mach 2 -
	Ling-Temco-Vought Corsair II A-7	38'9"	46'1-1/2"	715	578 mph
	McDonnell Douglas Phantom II F-4	38'5"	58'3"	900+	Mach 2 +
	McDonnell Douglas Skyhawk A-4A, B	27'6"	38'4-3/4"	2000	664/661 mph
	McDonnell Douglas Skyhawk A-4C	27'6"	39'1-3/4"	2000	649 mph
	McDonnell Douglas Skyhawk A-4E, F	27'6"	40'3-1/4"	2000	674 mph
	North American Rockwell Vigilante A-5	53'	75'10"	2650	Mach 2.1
	Northrop F-5A	25'3"	47'2"	368	Mach 1.4
	Northrop F-5B	25'3"	46'4"	380	Mach 1.36
U.S.S.R.	Mekoyan MIG-21("Fishbed")	~ 25'	~ 55'	375	Mach 2
	Mekoyan STOL ("Faithless")	~ 30'	~ 60'6"	NA	NA
	Mekoyan Variable Wing ("Flogger")	~ 50'	~ 57'	NA	NA
	Mekoyan MIG-23 ("Foxbat")	~ 40'	~ 69'	NA	Mach 3.2
	Myasishchev 201-M ("Bison")	~ 170'	~ 155'	5500	525 kts
	Sukhoi SU-7B	~ 30'	~ 56'	NA	Mach 1.6
	Sukhoi Variable Geometry SU-7	~ 41'	~ 56'	NA	NA
	Sukhoi SU-9 ("Fishpot")	~ 26'	~ 56'	NA	Mach 1.8
	Sukhoi Twin-Jet Interceptor ("Flagon "A")	~ 30'	~ 68'	NA	~ Mach 2.5
	Sukhoi Twin-Jet Interceptor STOL ("Flagon "B")	NA	~ 68'	NA	NA
	Tupolev TU-16 ("Badger")	110'	120'	3000 +	~ 587 mph
	Tupolev TU-22 ("Binder")	~ 80'	~ 130'	NA	NA
	Tupolev TU-? ("Fiddler")	~ 65'	NA	NA	~ Mach 1.75
	Yakovlev YAK-25 ("Flashlight")	~ 38'6"	~ 62'	NA	~ Mach 0.95
	Yakovlev YAK-28 ("Firebar")	NA	NA	NA	NA
	Yakovlev YAK-28 ("Brewer")	NA	NA	NA	NA
	Unidentified VTOL ("Freehand")	~ 34'6"	~ 55'	NA	NA
Yugoslavia	Soko G2-A Galeb (Seagull)	34'4-1/2"	33'11"	770	505 mph
	Soko J-1 Jastreb (Hawk)	34'8"	35'1-1/2"	945	510 mph

modern fighter aircraft, including fighters, interceptors, and fighter bombers, have one of the three following designs: (1) The first design is one which includes one or two engines mounted in the fuselage and a nose air-intake for a single-engine fighter (sometimes with the same general configuration as that for a two-engine fighter) or for a two-engine fighter where the intakes are mounted along each side of the fuselage ahead of the lead edge of each wing. Most have bubble canopies located on top of the fuselage and mounted ahead of the leading edge of the wings, and carry one or two crew members. Wings are of the swept wing type and may be either high, medium, or low wing. (2) The second design is the same as the first except that wings are of the delta design and horizontal stabilizers are normally lacking. (3) The third design is the multi-geometry fighter where the degree of wing sweep may be changed in flight for various operating missions and airspeeds. Although the United States has produced only one basic type (F-111) of the last design, several configurations based on the design principle have been built in the Soviet Union (namely the "Flogger" and the variable geometry SU-7) and in France (namely the Dassault Mirage G). Although extensively produced in the U.S.A. and the U.S.S.R., bomber aircraft, except for small light bombers and fighter-bombers, are not being manufactured in other countries.

There are three basic bomber configurations. The first (and most common in the U.S.A.) is one where the engines are mounted externally in pods from forward sloping pylons mounted on the lower wings. Bombers with this configuration have from two to eight jets (such as the B-66 and B-52). The second configuration is one where the engines are mounted underneath the wing but attached directly to it (such as the "Beagle"). And the third is one where the engine is mounted in the middle of the wing (for example, the "Bison" of the U.S.S.R. and the B-57 of the U.S.A.).

The wingspan of most fighters is between 30 and 40 feet and the overall length is between 40 and 70 feet (exceptions in both dimensions can be found). An analysis of seven types of light-attack bombers indicates that their average wingspan is approximately 65 feet and their average overall length is about 65 feet. The measurements for six medium bombers give an average wingspan of approximately 102 feet and overall length of about 107 feet. The average of the dimensions for two types of heavy, long-range bombers gives a wingspan of 177.5 feet and an overall length of 156.3 feet. Modern concepts favor the replacement of large slow bombers by bombers based upon large two-engine two-seat fighters with higher speeds in the Mach 2 range.

10.1.2.1 Aircraft Skin and Coatings

The aircraft skin is normally an aluminum alloy which may or may not have an external painted surface. If the aircraft is painted, its color, besides its identification and military markings, depends to a great extent on where it will be based. For example, many countries paint irregular shapes of brown, tan, green, or olive drab to the upper wings,

the sides and top of the fuselage, the fin (vertical stabilizer), and the upper sides of the horizontal stabilizers. A dark paint, usually a flat black, is normally found ahead of the bubble canopy. Such paint is intended to cut down the light reflected from the upper nose of the aircraft. Almost always land based, aircraft with such paint are so colored in order to break up their outlines and to blend their configurations with natural earth and vegetation when they are on the ground. Other aircraft are painted a medium gray on the upper and side surfaces; the underside of their wings and fuselage are usually a light gray or cream color, but often unpainted. Aircraft of this color normally operate outside combat zones or on aircraft carriers. Figure 223 shows a spectral reflectance curve for a weathered aluminum aircraft which was unpainted and Figure 224 presents the spectral emittance curve for an aircraft with a neutral finish.

10.1.2.2 Extrinsic Characteristics

The extrinsic characteristics of jet aircraft are their vapor trails at higher altitudes, their exhaust smoke at lower altitudes, and the heated airstream as the aircraft fly at high speeds. Exhausts from aircraft vary considerably depending on the number and type of engines, the use of afterburners, the nozzle design, the type of fuel, and the rate of burning. Winds, airspeeds, and exhaust-exit configurations determine the duration of these gases and the rate at which they cool as they are dispersed into the atmosphere. The transition from pure exhaust products to a mixture of exhaust plus air is rapid as the gases dissipate and the temperatures decrease.

10.1.2.3 Aircraft Data Sources

Data on the dimensions and types of military aircraft were gathered from Jane's All The World's Aircraft, 1968-1969 edition (Reference 37); and the Aircraft Recognition Manual, Nav Weps 00-80T-75, dated June 1962 (Reference 38). Data on extrinsic characteristics were found in pp 56-68, Handbook on Military Infrared Technology, 1965 (Reference 39); pp 81-91, Supplement 2 of the Handbook of Military Infrared Technology, 1967 (AD 585 778) (Reference 40); and a classified report entitled Special Camouflage Paint (U), dated 27 October 1967, by the Operational Test and Evaluation Force at Norfolk, Virginia (AD 385 323) (Reference 41).

10.1.2.4 Data Gaps

Spectral reflectance and emittance data for vapor trails and exhaust gases could not be found during this study. The number and type of aircraft for air and naval forces of several nations could not be obtained. This particular data should be available on a limited, classified distribution basis for military organizations. The missions of various types of aircraft would have been helpful in selecting the aircraft for this study. For example, an unclassified news release revealed that "Bison" (201-M) Russian bombers have flown directly from the Soviet Union to U.S. fleets and task forces in the Mediterranean and the Atlantic Ocean.

10.2 Backgrounds

A target background may be the sky or the surface material, depending upon the scan angle and field of view of the sensor. Materials comprising these backgrounds are those constituting the atmosphere, the oceans, and the land (shore). For example, in a surface-to-air mode, the sky will likely be the only background (here the sky is considered as an ether with energy emitted by its excited particles and chemicals and with energy transmitted, backscattered, and attenuated by it as the energy travels to the sensor's aperture). In an air-to-surface mode, only the sea will likely be a background, although the shore and/or the sky could be included as target backgrounds. In the surface-to-surface mode, all three background types could play a major part in the background scene.

10.2.1 Night Sky vs Zenith Angle

The night sky as a background consists of nightglow and tropospheric thermal radiation seen through the atmosphere as distributed sources of radiance. Stars appear as point sources. The spectral radiant intensity of the night sky changes with zenith angle because of the geometry of the curved-earth sources and the variation in atmospheric absorption. In a sky setting, a sensor views nightglow and senses radiation which corresponds to the spectral curves in Figures 225 through 234. The background tropospheric thermal energy for ten zenith angles is plotted in Figures 235 through 244.

The total starlight energy plotted in Figures 85 through 95 is not a true representation of the star energy because the stars are a series of point sources rather than a distributed source. Techniques to evaluate the star energy are presented by Chapman (Reference 42); however, his curves represent energies above the atmosphere. The spectral transmission curves in Figures 75 through 84 should be used to determine the spectrum of any particular star at the surface of the earth.

10.2.2 Sea Water vs Elevation Angle

The Handbook of Military Infrared Technology (Reference 39) contains on page 167 curves of the reflectance of sea water versus observation angle for the range between 1 and 14μm, see Figure 245. The Handbook of Chemistry & Physics, Vol. 41 (Reference 43) lists the index of refraction of water as 1.33290 which permits a reflectance calculation of 0.0203 at 0.55μm. This value corresponds to that for the 0° incident angle and the 1μm of the plotted curves in Reference 39. Accordingly, these curves were extrapolated to 0.2μm from 1μm by assuming that each curve has a constant value for this wavelength range. Figure 246 from page 167 (Reference 39) describes the effects of the incident angle integrated over the 1 to 14μm spectrum in emissivity and reflectivity. This curve was used to scale the 70° curve. Although the integrated reflectance apparently becomes 1 at 90°, no basis could be found

to predict the spectral shape at angles above 80° which seemed validated. Our 70° curve is an interpolation which seems reasonable, considering the data used. These four curves are presented in Figures 247 through 250 plotted to the scales of this report. Since Reference 39 assumes sea water to be opaque across the spectrum,

$$\epsilon = 1 - \rho \tag{23}$$

because

$$\tau = 0 \tag{24}$$

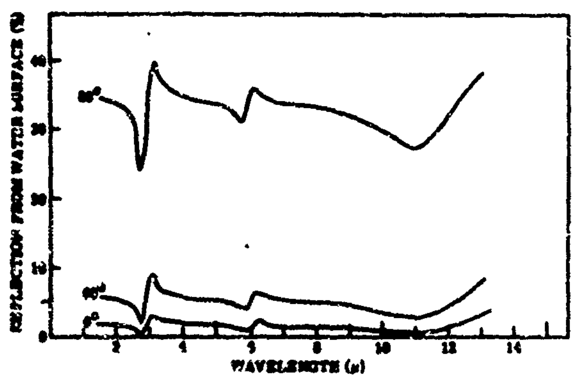
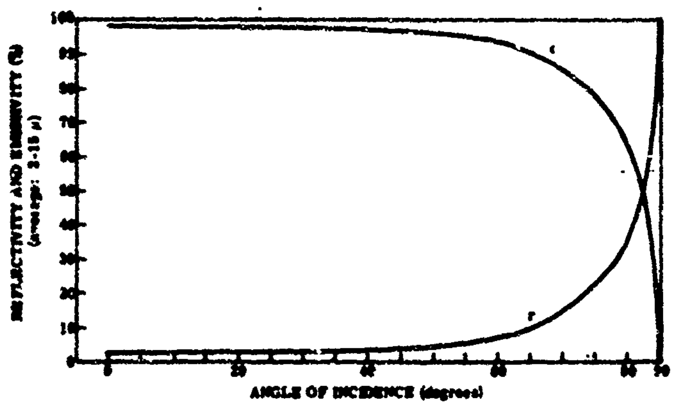


Figure 245. Spectral Reflectance of a Water Surface vs Angle of Incidence (Reference 39)

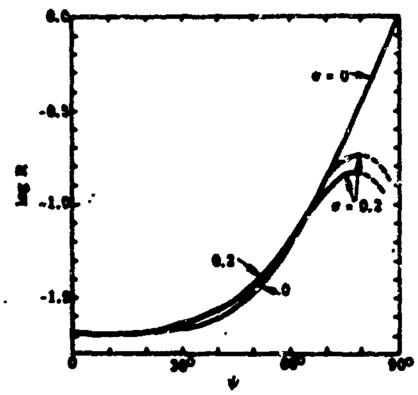


Note: Observe scale change

Figure 246. Average Spectral Emittance and Reflectance of Water vs Angle of Incidence (Reference 39)

10.2.3 Discussion of Sea State

The radiative properties of the sea surface obviously change with the sea state. The only directly useable data are reported in Reference 39. This report published the curve reproduced in Figure 251, which shows a dropping off of reflectance with observation angle for higher sea states.



Note: "σ = 0" denotes flat surface
"σ = 0.2" denotes Beaufort 4 wind (upper and lower values of theoretical calculations).

Figure 251. Effect of Sea State upon Reflectance vs Angle of Incidence (Reference 39)

The sea is normally a series of small waves superimposed upon larger waves. The wave periods range from inches to miles for fourier representations. An integrated reflectance could be calculated for a large sea area by considering each small, essentially "flat," radiating surface element making up the total surface. Each small element would have its unique angle of observation and its unique size and shape. However, this would be a formidable computing task. No precalculated data of this type could be located, except for that given in Figure 251.

10.2.4 Shore Backgrounds

For this study, the shore was defined as being composed of natural and man-made objects which extend from the shoreline inland some 5 to 10 miles or to the limit of the line of sight, whichever is less, and of those objects which extend seaward from the shoreline and are at or above the waterline during some part of a full day. Since these objects and the scene geometry could make up an infinite number of scenes, only a small number of generalized materials and types of scenes will be treated in the following paragraphs.

10.2.4.1 Landforms

Although unimportant in itself, landform is treated here to determine (1) the vertical area that the shore displaces in the scene of view and (2) the percentage of night sky illumination that falls upon the landform. These factors, of course, depend not only on the actual landform, but also on the range and angle of view of the sensor. In nearly all scenes, the shore will include a horizontal strip greater than the angular field of view of the sensor. There are many types of landform as indicated by the map Coastal Landforms of the World. This map is from Natural Coastal Environments of the World produced by the University of California (Reference 44). Since the map gives the landform for any area, it would be helpful in determining the scene geometry for a given area. If, however, a general solution is needed, then the landform can be generalized into the following three types: (1) gently sloping planes which normally intersect the sea and form a beach composed of sand with possible longshore bars of coral barrier reefs off shore, (2) hilly or mountainous terrain which intersects the coast line and forms either dissected sea cliffs or narrow rock- and boulder-strewn beaches interspersed with small pocket beaches of sand, and (3) a combination of (1) and (2) where a coastal plain develops shoreward from the mountains or hills.

10.2.4.2 Surface Materials

The surface materials consist of natural and man-made objects. In the following discussion, each of the selected objects is represented by a statistical set of reflectance and emittance curves. The representation of each of the natural materials in Figures 252 through 306 consists of three curves: the mean of the set and the ± one sigma values of the set. The unbiased estimate of σ is used here. And the representation of each of the man-made materials in Figures 307 through 325 consists of only one curve—the mean of the set—since the number of original curves for each of the man-made materials was insufficient to compute valid statistics. Whenever sets are said to be combined on a "one-to-one basis," each set is given equal weight, regardless of the number of original curves making up each set being combined.

10.2.4.2.1 Natural Surface Materials

Natural surface materials along the coast consist of organic and inorganic elements. Excluding animal life, the materials composing the shore background are vegetation, soils, and rocks.

10.2.4.2.1.1 Vegetation

Vegetation can be broken down into five basic types: tree foliage, both deciduous and coniferous; plants and shrubs; crops; grasses;

and barks and twigs. Normally, vegetation makes up the largest part of the shore background, particularly in the tropical and temperate areas of the world. In the temperate, subarctic, and some tropical areas, the season will determine whether the foliage is alive or dead.

10.2.4.2.1.1.1 Tree Foliage

The tree foliage consists of foliage from deciduous, tropical evergreen, and palmaceous trees. Although the amount of reflectance for different species varies, particularly in the visible spectrum, all the "broadleaf" trees have very similar spectral reflectance curves. Figure 252 represents the statistical set of several hundred reflectance curves for different live deciduous, evergreen, and palmaceous leaves. Figure 253 shows the emittance curves for the same type of tree foliage; however, the number of original curves in this set is less than that in the former. Figure 254 shows the reflectance curves for dead deciduous leaves. The comparison of Figures 252 and 254 shows the reflectance difference between live and dead tree foliage. From 0.55 to 0.68μm, the live foliage has a lower reflectance than the dead foliage; thus the leaves change from green to brown or red as they die. Live leaves have a strong absorption band which is centered at 0.68μm and is commonly referred to as the chlorophyll dip in the reflectance curve. Notice that the live tree foliage has a higher reflectance than the dead foliage in the 0.72 to 1.2μm range. After 1.2μm and up to 2.5μm, the dead vegetation reflects approximately twice the amount of energy that the live vegetation reflects. Coniferous needles have generally the same spectral curve shape as the broadleaf trees (see Figure 255). Figure 255 was prepared to represent many types of live coniferous needles. The comparison of Figures 252 and 255 shows, in general, that the coniferous needles have a mean value which is less than that of the broadleaves. Figure 256 represents a statistical set of reflectance curves for broadleaf and coniferous vegetation on a one-to-one basis. This is given to show live tree vegetation, in general, for unknown scenes.

10.2.4.2.1.1.2 Plants and Shrubs

Although plants and shrubs are broadleaf vegetation and should reflect approximately the same as broadleaf trees, some differences were found. Figure 257 represents a statistical set of reflectance curves for live plant and shrub vegetation. The comparison of these curves with those for the broadleaf trees shows plants/shrubs reflect more light in the 0.40 to 5.5μm region and about 3 to 7 percent less in the 0.72 to 1.3μm region. Figure 258 presents the set of the emittance curves for plants and shrubs, and Figure 259 shows the set of the reflectance curves for dead plants and shrubs.

10.2.4.2.1.1.3 Crops

Figure 260 presents the statistical set of reflectance curves for various cultivated crops. These curves very nearly match those for the

broadleaf tree foliage, with a small possible exception in the 0.72 to 1.3μm region where the crops have approximately 3 to 5 percent more reflectance than the broadleaf tree. The reflectance curves in Figures 261 are for dead crop leaves. The same general changes for live and dead broadleaf tree foliage are true for crop leaves, although the curves for the dead crop leaves have a greater range for ± one sigma in the 0.5 to 0.7μm region and again in the 1.2 to 2.5μm region.

10.2.4.2.1.1.4 Grasses

Reflectance and emittance curves for live grasses appear in Figures 262 and 263, respectively. Since only one emittance curve for live grass could be found, no sigma could be prepared for Figure 263. The dead grass reflectance curve in Figure 264 varies considerably from other dead vegetation. Although only one reflectance curve was available past approximately 1.15μm, the curve has no dips at 1.5 and 1.8μm as do the curves for other dead vegetation.

10.2.4.2.1.1.5 Bark and Twigs

The barks of both deciduous/evergreen/palmaceous and coniferous trees were treated together; the same was done for twigs of these trees. Figures 265 and 266 present, respectively, the reflectance and emittance curves for bark. A reflectance curve for twigs is shown in Figure 267. A statistical set of reflectance curves for bark and twigs on a one-to-one basis is represented in Figure 268. Although barks and twigs may generally not be a part of the background scenes, they will be a factor in the hardwood forest in the temperate zone during the late autumn to early spring and in the Monsoon forests during the dry season. A comparison of the bark and twig reflectance curves indicates the change in reflectance as the twigs become branches of the tree. From the near ultraviolet to 1.4 μm, the reflectance for the bark is considerably less than that for the twigs.

10.2.4.2.1.2 Soils

Soils are very difficult to classify either spectrally or any other way. Although soils are not an important part of the scene where vegetation flourishes, they play an important role in semiarid, arid, and subarctic regions. Reflectance and emittance characteristics of soil depend upon many factors, including color, texture, structure, chemical composition, and moisture. In classifying soils as to type, all the foregoing factors, except the last, are important. In this study color denotes that the soil is dark or light. Dark soils indicate a high percentage of organic material (humus) and nitrogen. Light-colored soils indicate lower amounts of humus material. Included in the latter are red and yellow soils which indicate iron compounds. Gray and white soils indicate reduced quantities of iron together with anaerobic decay of organic matter under poor drainage conditions. Brown

and grayish brown soils usually have some iron and humus content. Texture refers to the particle sizes found in the soils. Sizes of these particles are classified as follows: boulders, greater than 256 mm; cobbles, 64 to 256 mm; pebbles, 4 to 64 mm; granules, 2 to 4 mm; very coarse sand, 1 to 2 mm; coarse sand, 1/2 to 1 mm; medium sand, 1/4 to 1/2 mm; fine sand, 1/8 to 1/4 mm; very fine sand, 1/16 to 1/8 mm; silt particles, 1/256 to 1/16 mm; and clay particles including colloids, less than 1/256 mm. Since soils are a mixture of these various particle sizes, the soils must be further delineated as shown in Table 12.

TABLE 12

Soil Classified by Texture

Soil Texture Type	Percentage Sand	Silt	Clay
Sands	over 80	(together less than 20)	
Sandy loams	50-80	(together — 20 to 50	
Loams	30-50	30-50	less than 20
Silt loams	under 30	over 50	under 20
Clay loams	20-50	20-50	20-30
Clays	(together under 70)		over 30

Structure represents the arrangement of soil particles into clumps or aggregates after the soil has been broken up mechanically, such as by plowing. In light-textured soils, such as sand, texture is unimportant since these soils are made up of grains, not aggregates. Medium-textured soils such as the loams are favorable for plant growth, whereas the heavy-textured soils such as the clays are unfavorable for plant growth. Generally, chemical composition reflects that the soils have either a high acid or alkaline content. High acid type soils are caused mostly by low levels of lime. Because of the many independent factors in soil classifications, this study evaluated only moisture and texture, as summarized in Table 12. As far as moisture of the soil was concerned, the soils were either dry or wet. Medium-wet soils are represented when the data was available.

10.2.4.2.1.2.1 Clay

Figures 269 and 270 show, respectively, the composite reflectance curves for dry and wet clay soils. Figure 271 presents curves that are the composites of those in Figures 269 and 270. Because clays have the smallest particle sizes, their reflectance are not as much dependent upon texture as are the larger particles which make up the other soils. The moisture content is an important consideration, however.

10.2.4.2.1.2.2 Loam Clay

Figures 272 and 273, respectively, show the composite reflectance curves for dry and wet loam clay. Figure 274 presents curves that are the composites of those in Figures 272 and 273.

10.2.4.2.1.2.3 Loam Silt

Figure 275 shows the composite reflectance curves for dry loam silt. Although Figure 276 presents the same type of curves for medium-wet loam silt, its use is limited since it covers only from the near ultraviolet through the visible part of the spectrum. Figure 277 shows the reflectance curves for wet-loam silt soils. Figure 278 is a composite of Figures 275, 276, and 277.

10.2.4.2.1.2.4 Loam

Figures 279 and 280 show, respectively, the reflectance curves for dry and wet loam soils. Figure 281 is the composite of both dry and wet loam soil curves on a one-to-one basis.

10.2.4.2.1.2.5 Sandy Loam

Figures 282 and 283, respectively, present the reflectance curves for dry and wet sandy loam soils, and Figure 284 is the composite of Figures 282 and 283. These three figures are somewhat limited in their usefulness since they only cover the spectrum between 0.4 and 1.25 μm.

10.2.4.2.1.2.6 Loamy Sand

Figures 285 and 286, respectively, show the reflectance curves for dry and wet loamy sands. And Figure 287 is the composite of Figures 285 and 286. These soils differ from the sandy loam only in content of sand versus the silt/clay content. Since the sandy loam contains less sand than the loamy sand, the latter generally has a higher reflectance level in the shorter wavelength regions of the spectrum.

10.2.4.2.1.2.7 Sand

Of all the types of soils, sand is probably the most important since it will more likely be a part of background scene than all the other types. Sand appears most frequently in the form of beaches in the back shore area, and occasionally in the form of off-shore bars and coastal dunes. Figure 288 presents the reflectance curves for dry sand, and Figure 289 shows the emittance curves for dry sand. Figure 290 shows the reflectance curves for wet sand. Figure 291 is the composite of Figures 288 and 290 for the dry and wet sands.

10.2.4.2.1.2.8 Composite Soils

Of all the soil curves, the following will be most useful when the type of soil is unknown. These forthcoming curves are composites of all the previously mentioned soils. Figure 292 presents the composite reflectance curves for all dry soils except sand, and Figure 293 shows the composite emittance curves for all the dry soils except sand. Figure 294 gives composite reflectance curves for all wet soils except sand. Figure 295 is the composite reflectance of Figures 292 and 294 for all soils excluding sands. Figures 296 and 297 present, respectively, the reflectance and emittance curves for all dry soils including sand. Figure 298 displays the reflectance curves for all wet soils including sand. And Figure 299 is the composite of the reflectance curves for all wet and dry soils and sand.

10.2.4.2.1.3 Rocks

Rocks can normally be classified into one of three types: sedimentary, igneous, and metamorphic. Sedimentary rocks include sandstone, limestone, and shales. These rocks are formed by the cementing of sand, lime, and clays together under pressure. The igneous rocks are formed from molten rock which was pushed toward the surface of the earth but cooled and solidified before it became exposed at the surface. Metamorphic rocks are one of the first two types whose structure changed after it was originally created, normally under heat and pressure. Schist, slate, and marble are types of metamorphic rocks. Slate is shale which has undergone a metamorphic change, and marble is limestone which has undergone a similar change. Coral, although not a rock, but a living marine animal is included in this section by association. Figure 300 presents the reflectance curves for coral. Granite, a common rock found where mountains intersect the coast to form rocky cliffs, is represented by the reflectance curves in Figure 301 and by the emittance curves in Figure 302. Figures 303 and 304 present reflectance curves for sandstone and limestone, respectively. Figure 305 gives the composite of the reflectance curves for many types of rocks (not just the above) and Figure 306 offers the composite of the emittance curves for many types of rocks.

10.2.4.2.2 Man-Made Construction Materials

Materials in this section will deal with concrete, masonry, asphalt, glass, ferrous metals, and wood.

10.2.4.2.2.1 Concrete

Reflectance curves for concrete and cement are shown in Figures 307 through 310. The cement and concrete represented here are used as building materials. The curve in Figure 308 represents a sample of concrete that was part of a runway that had been weathered 24 years.

This curve has somewhat less reflectance than the other curves, probably due to rubber and oil that has accumulated on the surface over the years.

10.2.4.2.2.2 Masonry

Reflectance curves for a light-yellow brick, a medium-brown brick, cinder block, and terra cota building materials are shown in Figures 311 through 314, respectively.

10.2.4.2.2.3 Asphalt

Asphalt is found most commonly in road beds; however, asphalt type of shingles for roofing and flat-industrial type of roofs with stone over asphalt are commonly used as construction materials. The curve in Figure 315 represents an aged asphalt base roof shingle which was a reddish brown. Figure 316 is a reflectance curve for an asphalt road.

10.2.4.2.2.4 Glass

A reflectance curve for glass is shown in Figure 317. Extreme care must be used when using this curve since it is a diffused reflectance curve. Although all reflectance and emittance curves in this report with the exception of water are diffused curves, glass will have great fluctuations particularly when viewed near the norm since it is a specular reflector.

10.2.4.2.2.5 Ferrous Metals

Iron, steel, and steel alloy vary considerably over the spectrum. Examples are emittance curves for iron in Figure 318 and for a corrosion-resistant steel in Figure 319. Reflectance curves for galvanized iron in Figure 320, rusty iron in Figure 321, and rusty steel in Figure 322 are included to indicate the reflectance characteristics of other forms of ferrous materials. Galvanized roofs are fairly common in some areas. When such roofs are not properly maintained, the resultant rust will change the spectral reflectance of the basic material.

10.2.4.2.2.6 Wood

Wood is a very common building material, especially in underdeveloped areas. Since it is normally protected by paint or other covering, its reflectance and emittance values would be for the protective coating rather than for the wood itself. The only reflectance curves available for wood, other than those shown in Figures 220 through 222 under the target section of this report, are as follows: Figure 323 for creosote dipped wood, Figure 324 for a smooth freshly sanded piece of plywood, and Figure 325 for an old weathered piece of plywood.

10.2.4.3 Global Location of Surface Materials

When the shore is part of the background scene, its rural or urban character should be considered. If it is rural, which it would most probably be under a random sampling, the latitude, if not the longitude as well, should also be considered. Of course, natural materials will make up the rural scene, and man-made construction materials will predominate in the urban scene.

10.2.4.3.1 Natural Materials

Knowledge of the latitude, if not the longitude as well, is especially helpful in determining the vegetation in the background scene. Such knowledge along with information of the coast (east or west), regardless of the landmass, permits generating a "typical" scene. Table 13 is a generalized listing of the vegetation types which appear world-wide, and Table 14 describes each of these vegetation types along with an identification number to be used as a key when referring to Figure 326, the Coastal Vegetation of the World Map (see Reference 44). Through Tables 13 and 14 or Figure 326 and Table 14, the more logical combinations of live and dead vegetation may be determined for a specified location. Table 15 shows the vegetation found between the Arctic and Antarctic Circle by both mileage and as a percentage of the total. Although the number of miles for each type of vegetation is lacking somewhat in accuracy and may be significantly low in mileage due to use of a small globe, the relative percentages should be very close to the correct figure.

TABLE 13

Major Vegetation Types by Coast and Latitude

Latitude	West Coast
Arctic Circle to 58°N	Aleutian
58°N to 38°N	Oregonian or Virginiar
38°N to 30°N	Mediterranean
30°N to 22°N	Sonoran
22°N to 20°-15°N	Tampicoan or Tamaulipan
15°-20°N to 5°-10°S	Timoran, Nicaraguan, or Malayan
5°-10°S to 8°-24°S	Sonoran
8°-24°S to 32°S	Atacaman
32°S to 38°S	Mediterranean
38°S to 40°S	Kyushun
40°S to 55°S	Tasman

Latitude	East Coast
Arctic Circle to 55°-60°N	Aleutian
55°-60°N to 48°-44°N	Alaskan
48°-44°N to 38°-34°N	Virginian or Oregonian
38°-44°N to 27°-22°N	Kyushun
27°-22°N to 30°S	Tampicoan, Tamaulipan, Timoran Nicaraguan, or Malayan
30°S to ---	Varies greatly as to each specific area.

TABLE 14

Coastal Vegetation

Identification Number	Vegetation Class	Vegetation Type	Description
1	Desert	Atacaman	Barren dese. Little or no vegetation. Original rock or sand colors predominate.
2	Desert	Patagonian	Cold desert. Occurs on the southern Atlantic coast of Argentina. The vegetation consists largely of widely spaced stunted bushes that range from 3 to 8 or 10 feet high, are mostly thorny or scrubby, and vary greatly in shape. Basins and gulches are generally salt-laden tracts. Bitter cold winters and hot dry summers with suddenly rising winds.
3	Desert	Sonoran	Subtropic desert. Similar to the thorn forest areas but differing by the amount of numerous shrubs and small trees. Spacing varies from widely scattered in the drier parts to relatively close in the more humid areas. Such trees that do exist are normally found in dry washes. Rains are infrequent.
4	Grassland	Aleutian	Tundra and polar barrens. Treeless landscapes characterized by dwarf herbs, grasses, mosses, and lichens which only partially cover the ground during the summer. The changes which occur seasonly are considerable. Winter, of course, is white with snow and ice; spring is brown from the bare soil, late spring and summer brings the greens of the arctic flora.
5	Grassland	Tripolian	Short grass, desert grass. This is a shorter grass than the Argentinean type generally found between the Mediterranean and desert areas. This grass is generally found in dispersed clumps reaching a maximum knee-deep height.
6	Grassland	Argentinean	Prairie. Occurs in warm temperate to temperate climates between the temperate forests and the short grass desert environments. Grass may grow to waist height but is commonly shorter.
7	Grassland	Visayan	Tropical grasslands. Very local type of vegetation found throughout the tropical areas. Very similar to the tropical savannas but generally occur where more moisture is available. The grasses differ from the savannas, however, in that they average 5 to 7 feet in height, but may reach heights of 12 feet. These blades of grass are wide, coarse, and fibrous, but their most striking characteristic is their razor-sharp saw edges.
8	Evergreen Srubland	Mediterranean	Sclerophyll woodland and shrub. A unique and widely occurring vegetation type found on both equator sides at the middle latitudes but only on the west coasts of continents (if the Mediterranean Sea Area is considered such). From a distance it appears rather a meager type of vegetation, but upon close inspection one finds that it is composed of dense and nearly impenetrable much-branched shrubs and small trees, 3 to 13 feet in height. The stiff branches are fairly regularly interlaced. Examples are the chaparral of California and macchia or garigue of the Mediterranean area. The live or green oak predominates in these areas, and in some areas, where water moisture is more abundant, there are larger trees ranging up to 50 feet in height. The dryer areas are more like the Tamaulipan areas.
9	Temperate Forest	Tasman	Subantarctic forest. Similar to its counterpart the Oregonian forest of the northern hemisphere, but with less variety of deciduous trees. The conifers are smaller than those found in the northern hemisphere conifer forests but are more densely spaced than their counterparts.
10	Temperate Forest	Alaskan	Taiga forest. A stunted conifer forest with isolated stands of deciduous trees, such as aspen, cottonwood, and birch (whicy may be locally dominant), which attain a height of 50 to 80 feet at the lower latitudes and degenerate into small trees and shrubs in the northern subarctic regions. Meadows are interspaced throughout forest and create boggy quagmires in the summer. In the subarctic northern regions muskeg penetrates much of the taiga forest.
11	Temperate Forest	Oregonian	Conifer forest. These forests consist of conifers varying anywhere from 100 to 200 feet in height, and where there is excessive precipitation, such as the Olympic Peninsula, the undergrowth becomes nearly as dense as that found in the tropical rain forest.

TABLE 14

Coastal Vegetation (concluded)

Identification Number	Vegetation Class	Vegetation Type	Description
12	Temperate Forest	Virginian	Mixed deciduous and conifer forest. These forests consist of mixed deciduous hardwoods and locally predominate conifers such as pine. To the south this type of forest grades into the Kyushun type, and to the north it grades into the pure conifer or taiga forest. Trees are 80 to 100 feet in height and moderately to closely spaced. Undergrowth varies from little or none to very dense depending on soil and spacing of the trees.
13	Temperate Forest	Kyushun	Warm temperate rain forest. This is an evergreen forest of the temperate climates which under favorable climates merges with the tropical rain forests. The trees are somewhat smaller than those found in the tropical rain forest, and they have smaller leaves.
14	Tropical Shore Woodland	Irrawaddyan	Mangrove, Nipa Palm, Beach jungle. Consists of two basic types. The first is the type that grows as a beach woodland along the upper beach zone or backshore and in swampy fresh water areas. These trees are of moderate height growing to 30 to 40 feet, with large leathery leaves. The second type is the tidal woodland where the trees grow in water adjacent to the shore. These trees are not limited to, but are predominately, the mangrove. Nipa palm also is a major type but is normally found in the brackish waters of tidal estuaries and fresh/salt marshes. Both types present a very formidable barrier. They occur on the coast in front of many other types of coastal vegetation, such as identification numbers 19, 18, 17, 16, 15, and swamps. They have even grown off desert areas such as the Arabian coast facing the Red Sea.
15	Tropical Scrub	Tampicoan	Thorn forest or thorn scrub. A dense scrubby forest of large shrubs and scattered trees up to 30 or 40 feet in height. Very close spaced, hardwood, deciduous thorn shrubs are predominate and nearly impenetrable. Rainfall 15-30 inches annually with hot humid summers (rainy period) with cool, mild, dry winters.
16	Tropical Savanna	Tamaulipan	Desert savanna. Consists of grasses with intermittently dispersed dwarf trees. Grasses reach a height of about 3 feet. Found between tamaulipan on one side and tropical deserts on the other. Rainfall amounts to 15 to 30 inches annually.
17	Tropical Savanna	Timorran	Savanna forest or Woodland. Consists of tall grasses with interspersed trees or small woods. These trees are of the "umbrella" type with thick and gnarled trunks and branches which shed their leaves during the drought periods. These areas are localized rather than regional. Annual rainfall is 30-50 inches. Tropical Savannas are the transitional areas between the tropical forests and the tropical deserts.
18	Tropical Forest	Nicaraguan	Deciduous or Monsoon forest. Similar to Malayan type, however, rains are seasonal thus leading to dry periods where both the trees and undergrowth are void of foliage. Because of these periods of drought, the undergrowth is much more dense and nearly impenetrable while the upper canopy is not nearly so continuous thus allowing both ground undergrowth and an under canopy of smaller growth consisting of palms and bamboo thickets to develop. Upper canopy reaches a height of 80 to 100 feet. During wet season 50 to 70 in. of rain are received and it is similar to the evergreen forest.
19	Tropical Forest	Malayan	Evergreen rain forest. Dense evergreen tropical forests are those whose thick canopy of leaves and branches exclude much of the sunlight, thus inhibiting the undergrowth. Forest ceiling is nearly continuous and between 100 to 140 feet in height. Soil is clayey. 100+ in. of rain annually.
S/M	Swamps/Marshes	---	Salt water swamps and marshes which do not have Irrawaddyan types of vegetation.
SF	Salt Flats		Salt flats caused by tidal conditions where salt water evaporates on a plain leaving almost pure salt.

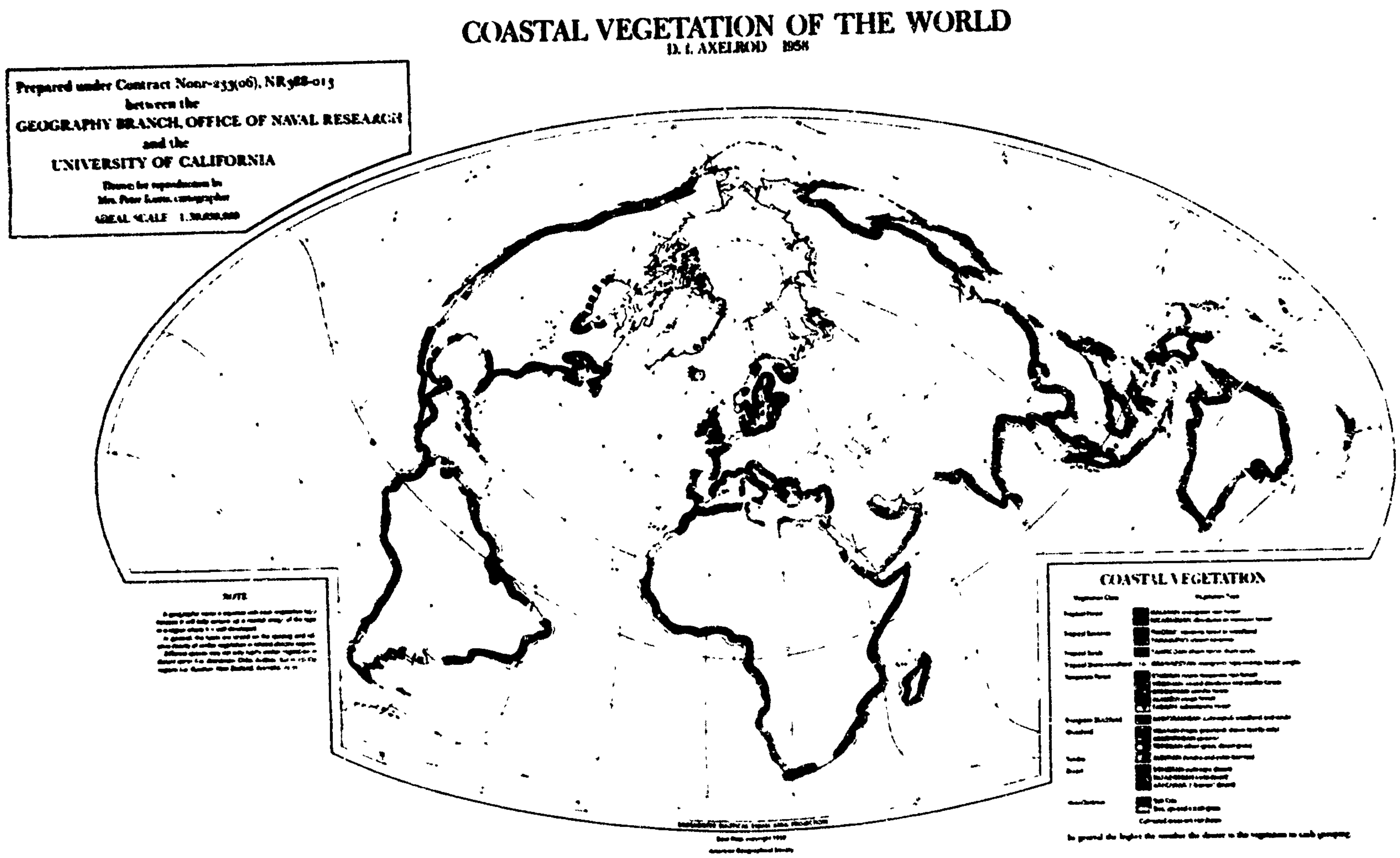


Figure 326. Map of the Coastal Vegetation of the World

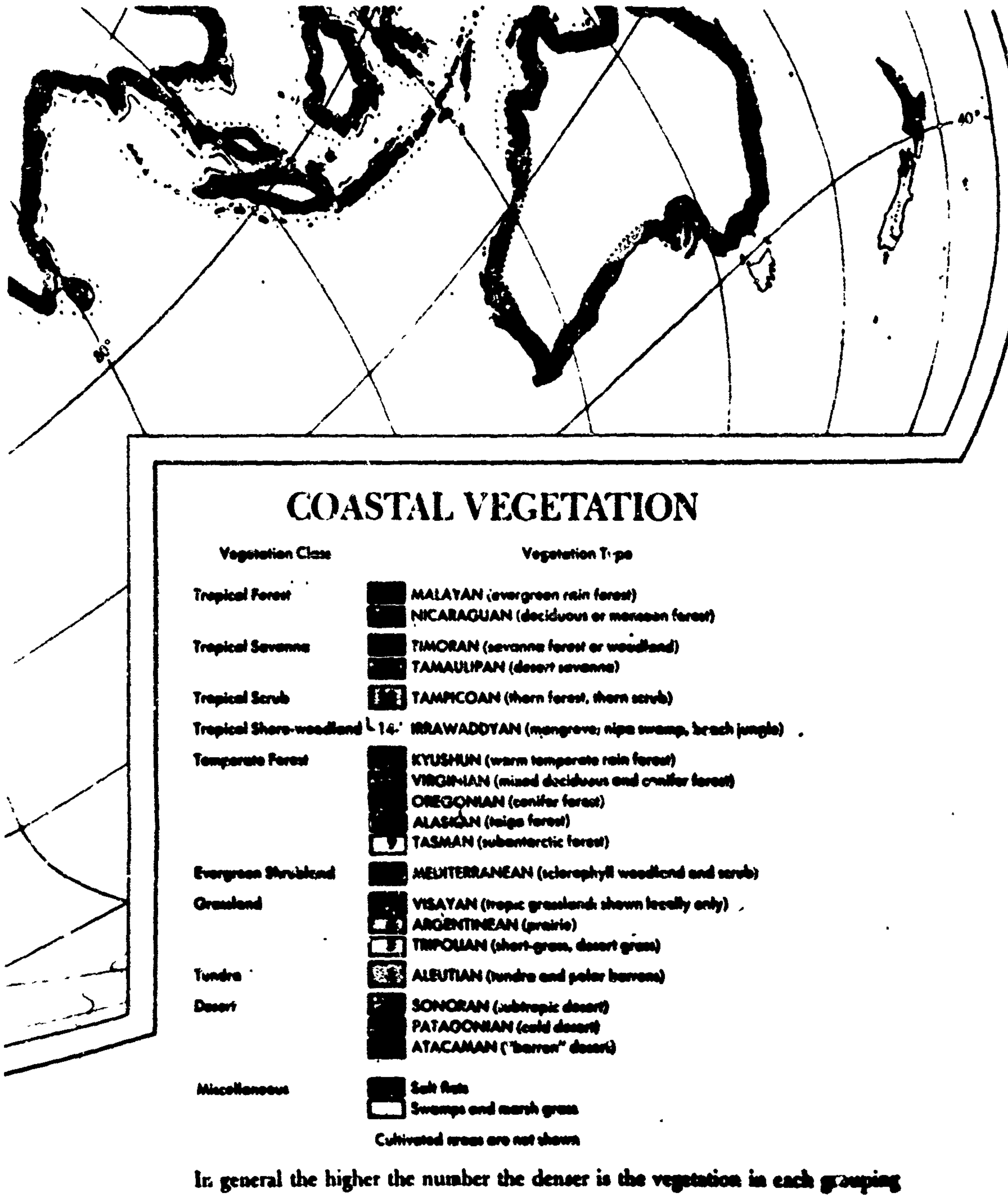


Figure 326. Map of the Coastal Vegetation of the World (cont'd)

TABLE 15

Types of Coastal Vegetation by Percentage of Total
(Vegetation Type Number Corresponds to Identification Number in Table 14)

Vegetation Identification No.	Percentage	Number of Miles of Coastline
19 w/14	21.29	37,325
4	10.27	17,995
12	9.41	16,500
8	9.30	16,300
17 w/14	8.36	14,655
10	5.86	10,280
13	5.42	9,495
18 w/14	4.74	8,315
3	3.60	6,310
16	2.99	5,240
9	2.48	4,350
5	2.24	3,925
1	2.20	3,860
11	1.85	3,235
15	1.52	2,660
15 w/14	1.43	2,500
6	1.13	1,980
7 w/14	1.07	1,880
S/M	1.02	1,785
18	.90	1,570
19 w/14 & S/M	.85	1,485
2	.68	1,190
SF	.34	595
19	.31	535
S/M w/14	.29	500
17	.17	300
16 w/14	.15	265
3 w/14	.13	230
17 & 19 w/14	.02	30
Total		175,290

Note: Accuracy on map could be measured only to the nearest 30 or 35 miles.

10.2.4.3.2 Construction Materials

Excluding architectural pecularities, man-made construction materials vary little in urban areas around the world, for even undeveloped countries either trade for finished building materials or have the capability of producing their own. Although rural areas may principally use locally available materials, notably wood, the natural materials, not the man-made ones, will dominate the rural scene.

10.2.4.4 Surface Material Data Sources

10.2.4.4.1 General

The data on the reflectance curves discussed in this section were taken from the University of Michigan data bank as they appear in absolute format for the Air Force's Target Signature Program. These do not agree with those published by the University of Michigan because their data are relative reflectance rather than absolute reflectance, in many cases. The emittance curves were obtained from the Compilation of Spectral Emittance of Background and Target Constituents in the 8- to 14-Mission Range (Reference 19). The discussion of various types of soils was based on Appendix B, A Regional Economic Geography (Reference 45). The data on the coastal vegetation types were derived from Natural Coastal Environments of the World (Reference 44) and Coastal Geography Conference (Reference 46).

10.2.4.4.2 Processed Data

The reflectance and emittance curves presented in the sections on natural materials represent the statistical groupings of many original individual curves. For example, the curve for the tree foliage (composite of deciduous, tropical evergreen, palmaceous, and coniferous foliage) represents some 900 separate curves. The result of each grouping is called a statistical set which consists of three curves: a mean of the set and the ± one sigma of the set. Figure 327 illustrates how the sets were derived. However, the reflectance and emittance curves presented in the sections on man-made construction materials do not represent statistical groupings because of the insufficiency of the original individual curves; for example, the four composite cement/concrete curves represent fewer than 20 separate curves. Note that all reflectance data published herein is absolute reflectance, rather than relative to the measurement standard as published in the work of the University of Michigan.

10.2.4.4.3 Data Gaps

There is very little emittance data for either natural or man-made objects; moreover, the available data is generally not continuous from 0.2 to 14.0μm. Although more data is available for spectral reflectance, most of the represented materials, both natural and man-made, are found only in the Continental United States, Hawaii, Puerto Rico, or Cuba (one soil type). Although the given vegetation curves likely represent world-wide vegetation, there are many other species of vegetation whose measurements have not been acquired to either confirm or deny this assumption. Another gap exists for directional reflectance data over the given spectral region. There are some isolated examples of directional reflectance and emittance data for one or two specific wavelengths, but they are far from continuous. For most materials,

lambertian surfaces can be safely used; however, materials such as water, glass, and polished metals are highly specular in nature.

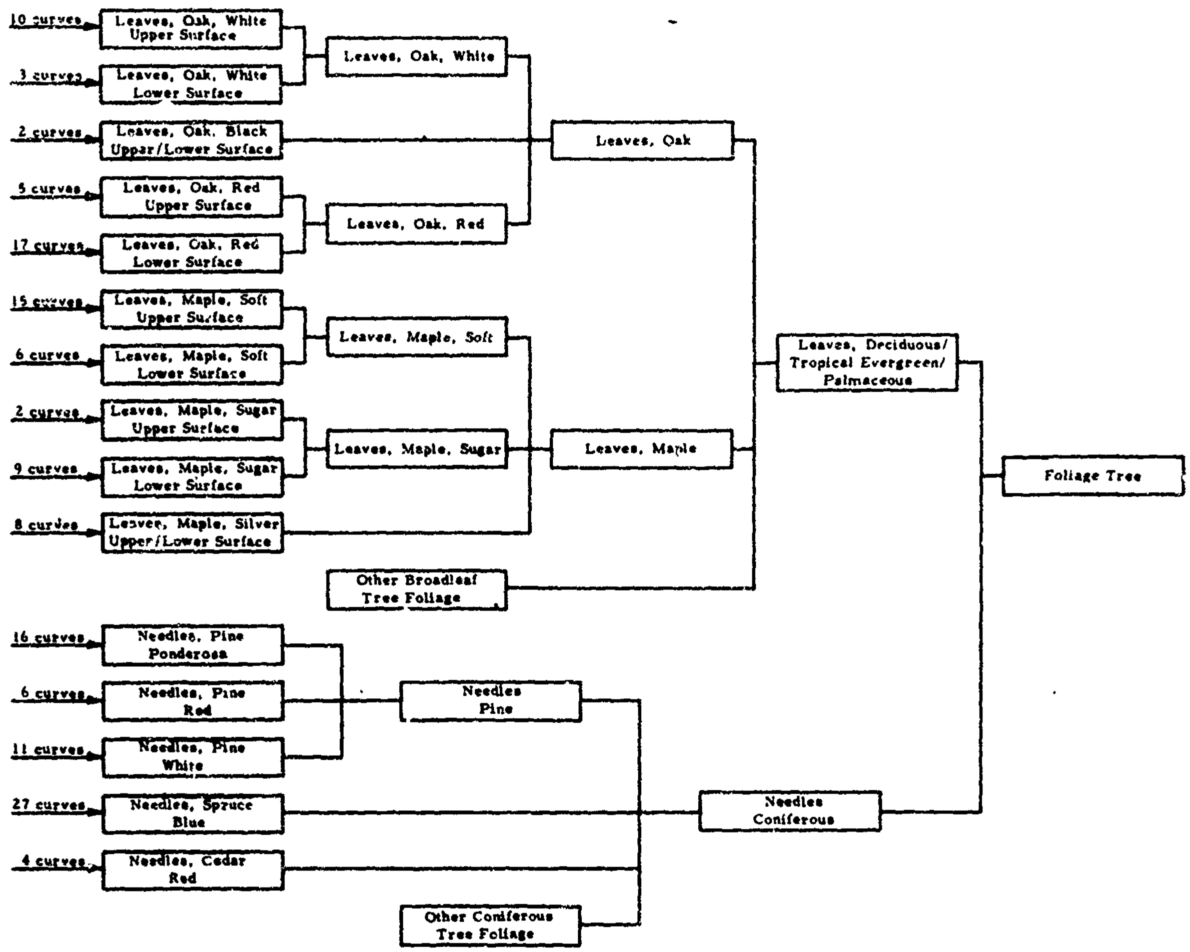


Figure 327. Flow Diagram of Data Manipulation to Develop Sets (Abbreviated Example for Tree Foliage)

11. Summary and Conclusions

This research was directed toward the assembly of data describing naval targets and backgrounds for studies of night sensing systems. The classified and open literature was searched, and all known data sources were contacted for unpublished data. A library of 639 documents was assembled. The best available data for target scene materials specification are reported herein. Emittance and reflectance data were collected for the most important materials across the complete spectrum from 0.2 to 14.0μm. A few extrapolations were made to extend incomplete data, with as much cross-checking as possible being done to validate these calculated values.

Many types of data had to be assembled from many different and variegated sources. Most of this effort was expended in finding the data and determining how to convert it into consistent, useful, and valid units. Much desired data is incomplete or missing. The calculations presented herein represent a first attempt at providing a complete set of data in one document.

The principal illumination sources were determined to be the moon, stars, nightglow, and tropospheric thermal radiation. Each of these was studied to quantify their radiation into consistent and absolute values of radiometric units such as spectral irradiance in watts per square meter. The total spectral energy from each source to the earth's surface was calculated for horizontal and vertical surfaces. This calculation was based on the selective transmission of a model US Standard Atmosphere with Elterman's particle distribution added, which should be reasonable for sea conditions on clear nights. The selective atmospheric spectral transmission as affected by water vapor, carbon dioxide, ozone, and scattering particles was calculated for various zenith angles. The night sky as a background was also calculated.

All data are presented as a series of plots generated by a computer. Materials are represented as reflectance or emittance versus wavelength. Energy is represented as radiance or irradiance versus wavelength. Atmospheric transmission is represented as transmittance versus wavelength. All data used are in radiometric units, and all plots have consistent scales for ease of reading. This data can be used to evaluate the utility of any part of the spectrum from 0.2 to 14.0μm for naval night sensing. This report provides a consistent evaluation of one band (visible, near IR, far IR) against another because the same calculation techniques are used for each part of the spectrum and compatible units are used throughout.

Data to describe the radiative effects governing night naval sensing are available with sufficient quantity and quality to support useful analyses. The reported results will serve as a basis for further expansion and refinement.

12. Recommendations

To improve upon the data presented in this report, three specific efforts are recommended: First, certain missing or incomplete measurements should be made. Second, these data should be combined with a sensor simulation model to evaluate actual system performance. Third, a set of refined calculations should be made for each of the night-sensing phenomena; such calculations should include a finer spectral resolution for a large number of specific naval targets, backgrounds, and sensor systems.

In addition, new data should be measured to fill gaps, and refined calculation techniques should be applied to permit complete sensor system evaluation.

CALCOMP PLOTS

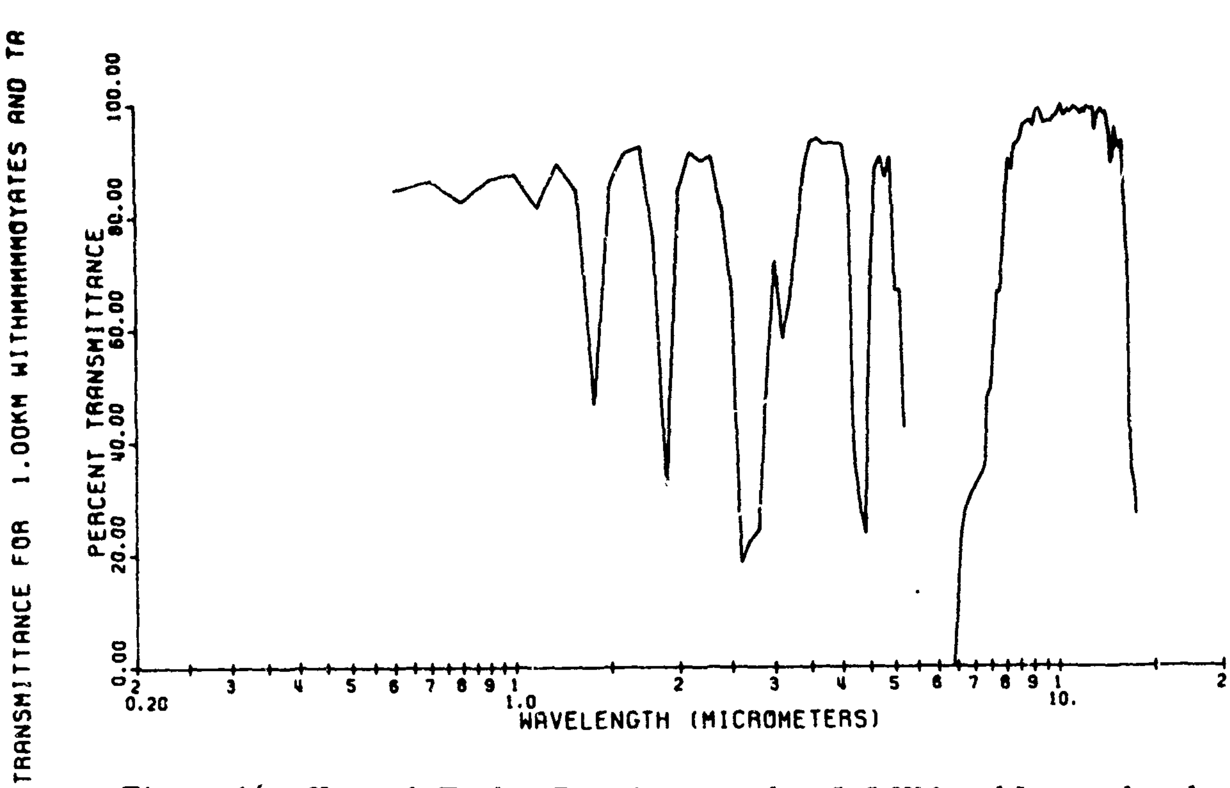


Figure 16. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 1 KM

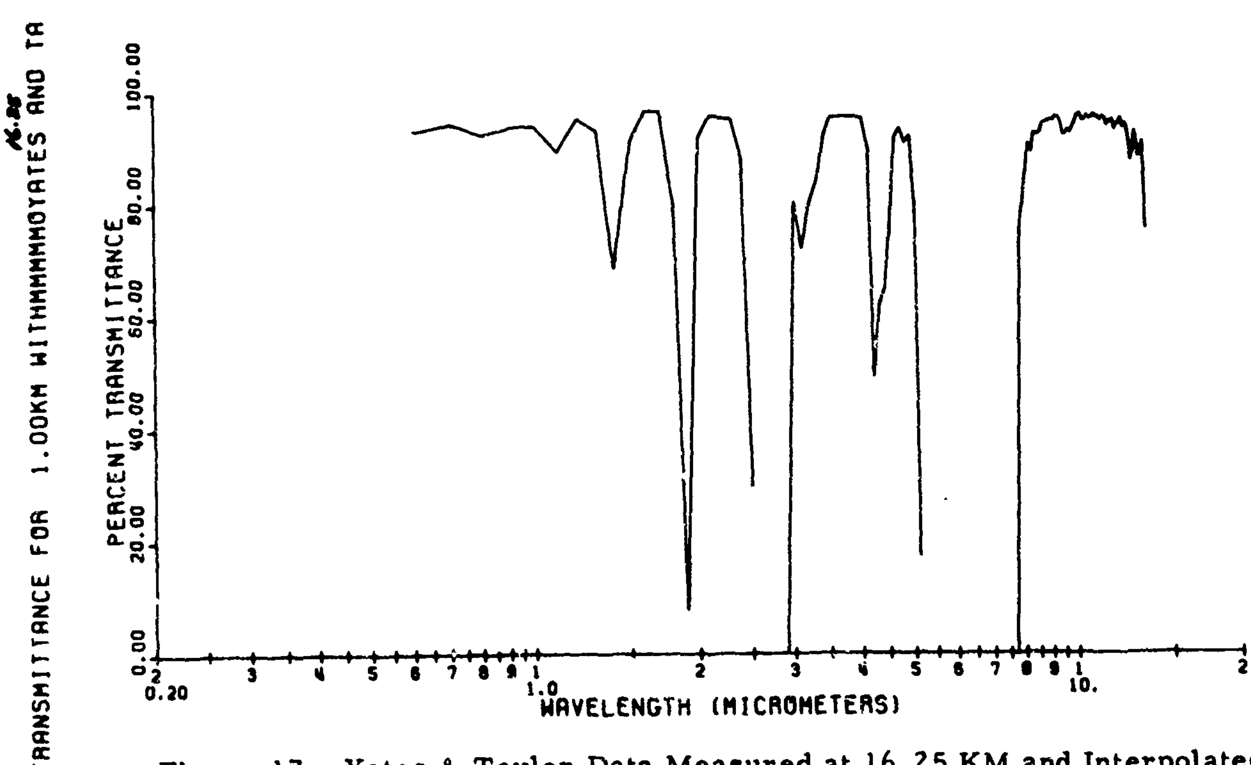


Figure 17. Yates & Taylor Data Measured at 16.25 KM and Interpolated to Range of 1 KM

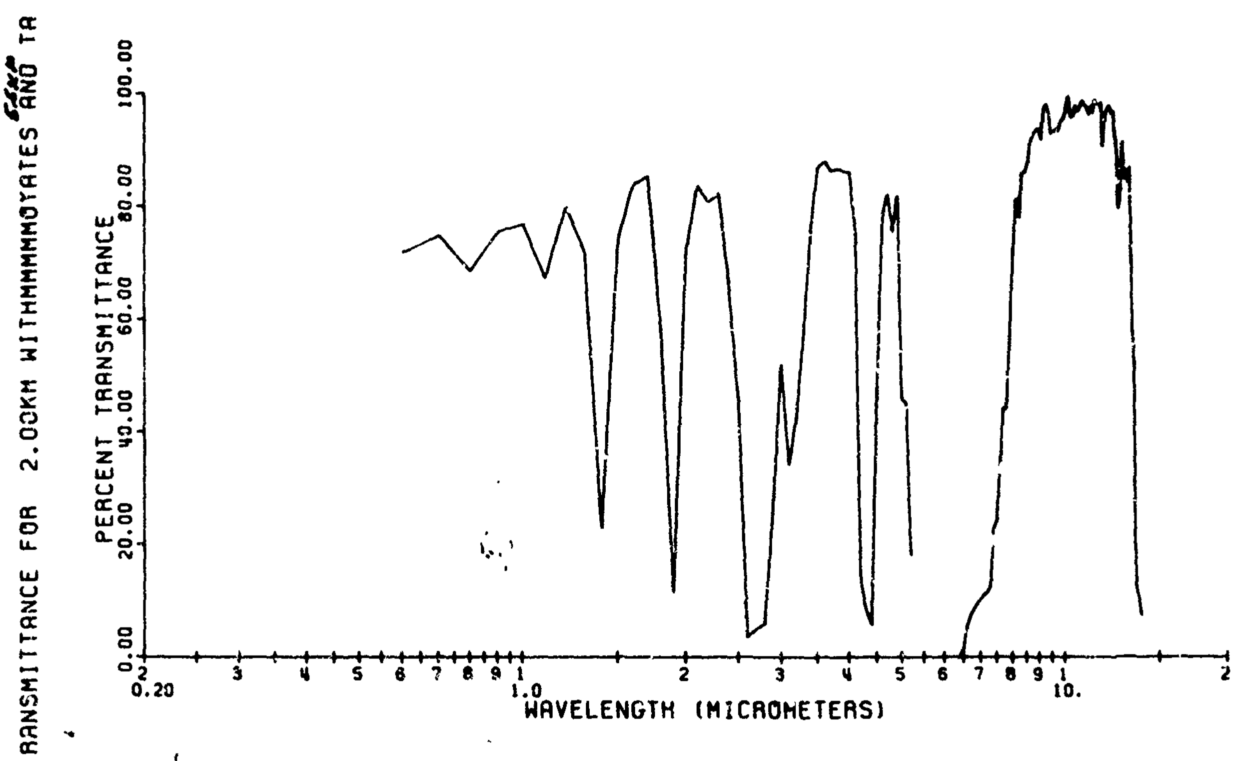


Figure 18. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 2 KM

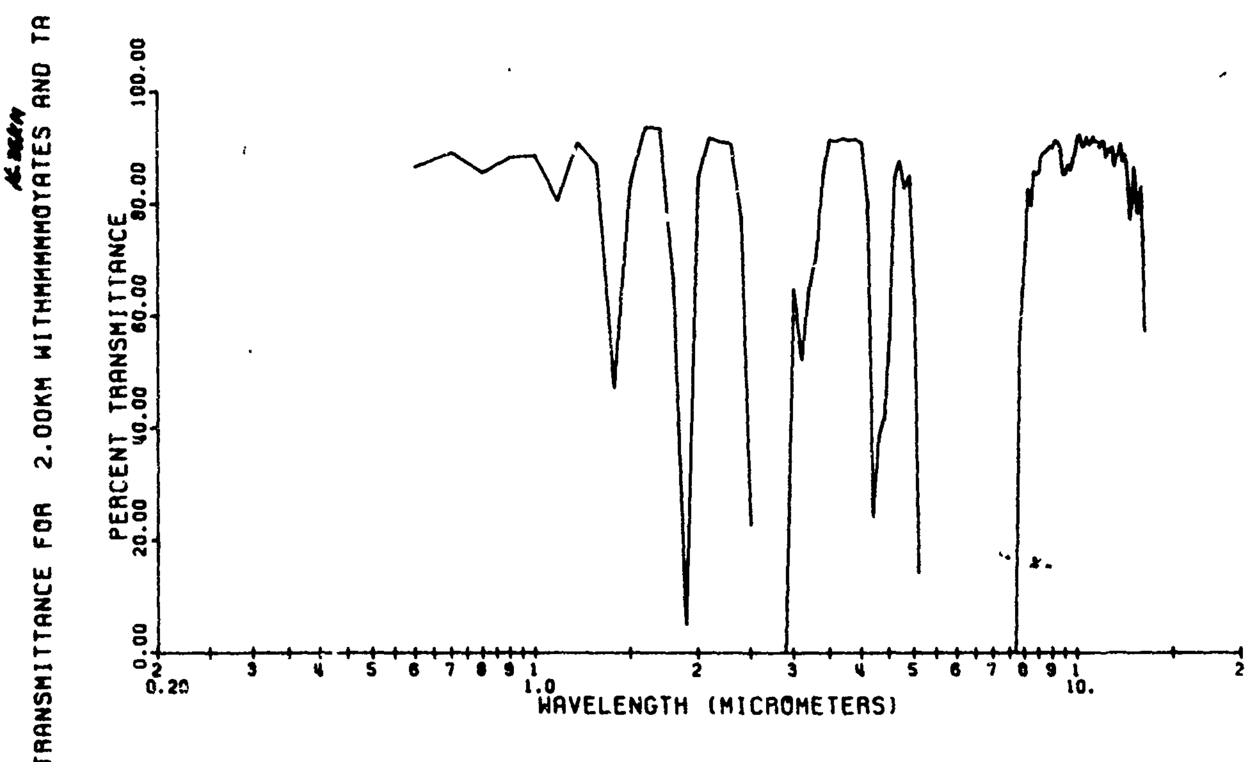


Figure 19. Yates & Taylor Data Measured at 16.25 KM and Interpolated to Range of 2 KM

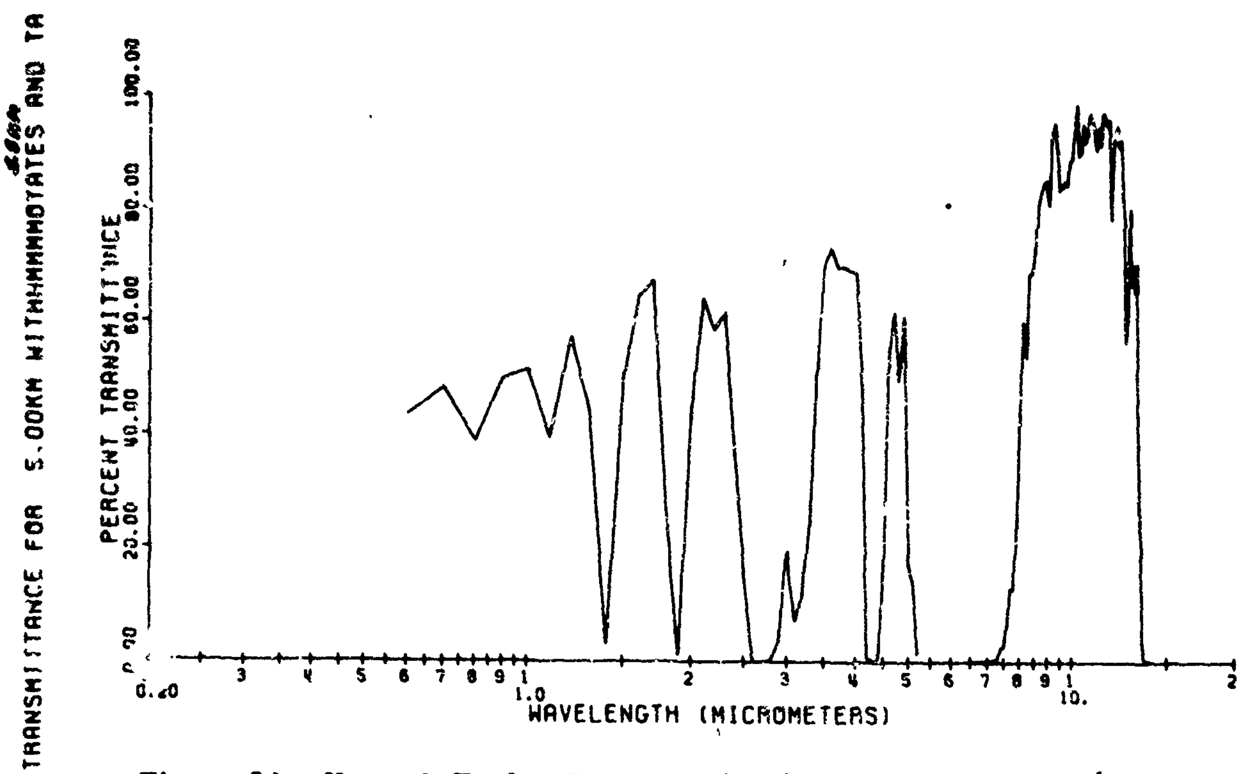


Figure 20. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 5 KM

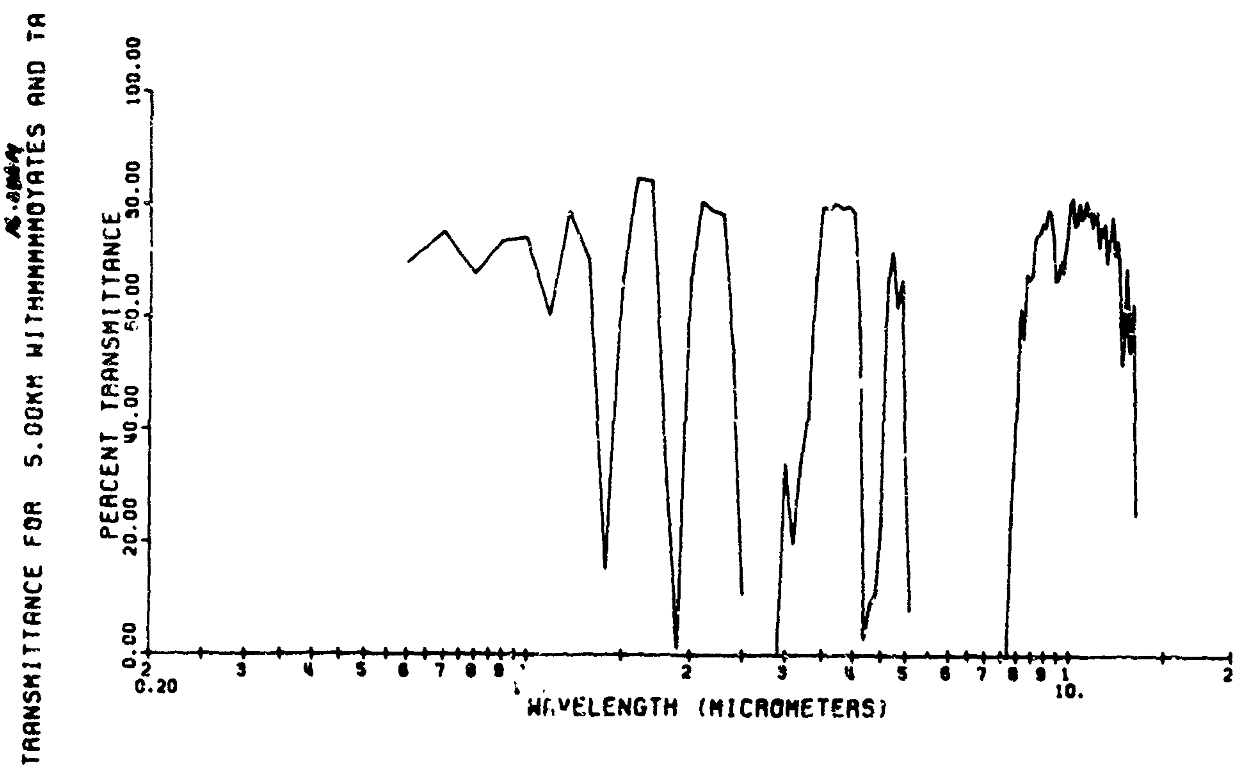


Figure 21. Yates & Taylor Data Measured at 16.25 KM and Interpolated to Range of 5 KM

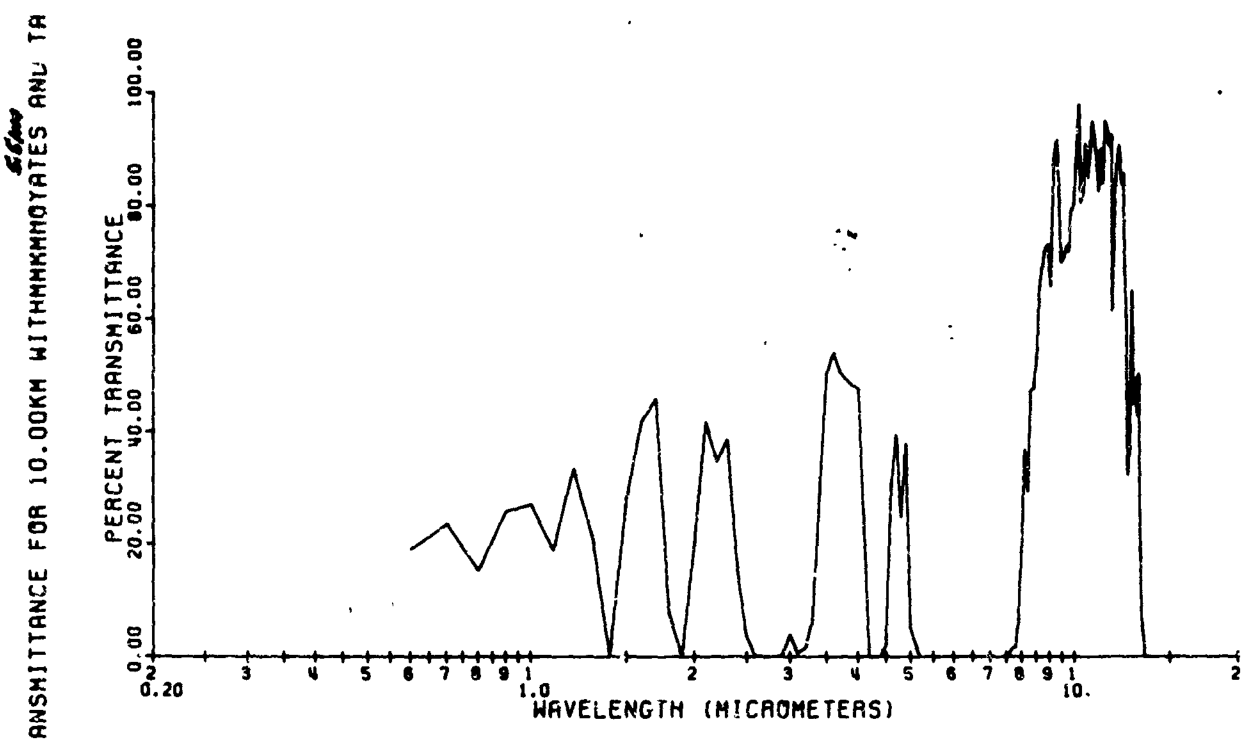


Figure 22. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 10 KM

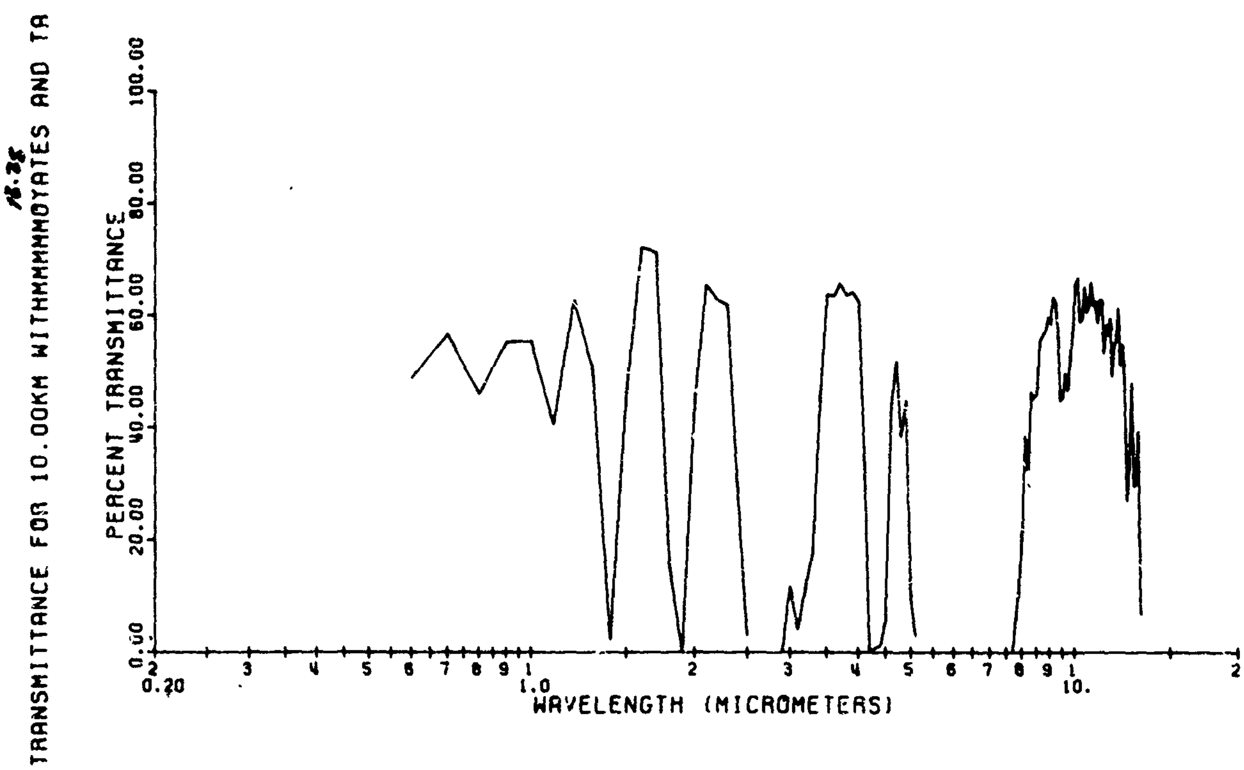


Figure 23. Yates & Taylor Data Measured at 16.25 KM and Interpolated to Range of 10 KM

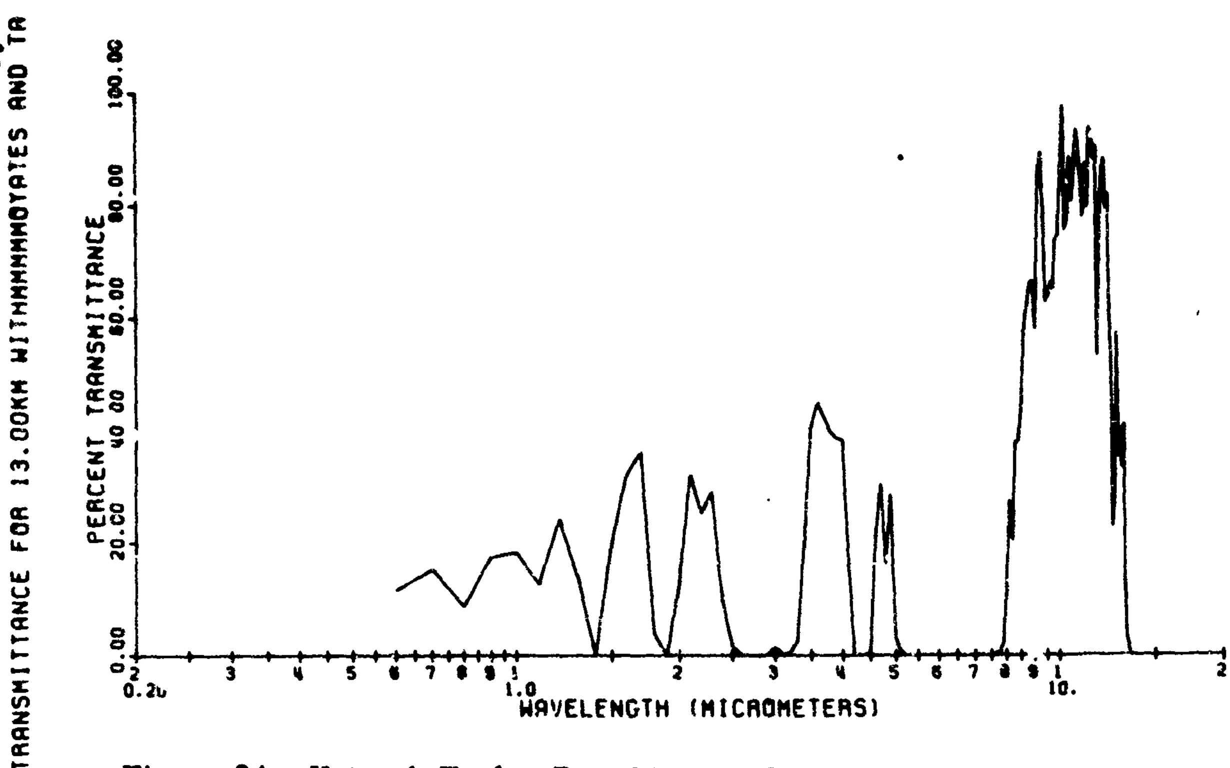


Figure 24. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 13 KM

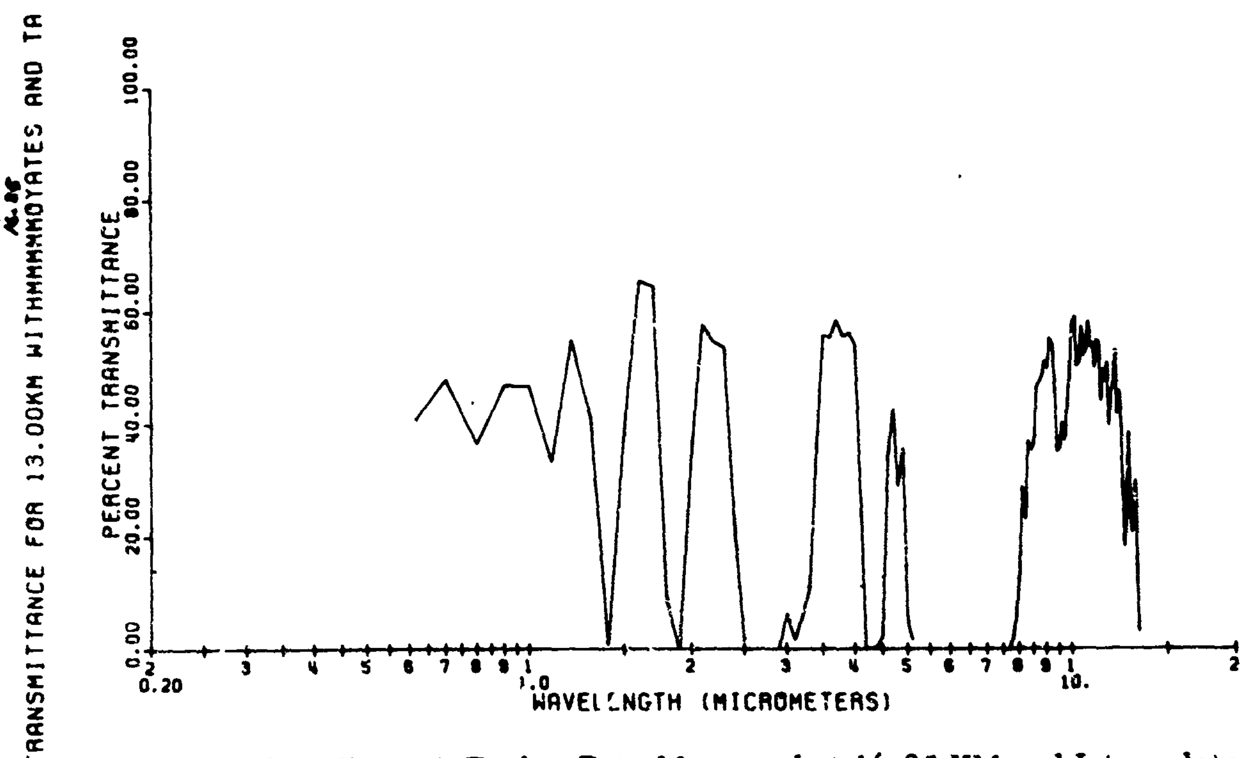


Figure 25. Yates & Taylor Data Measured at 16.25 KM and Interpolated to Range of 13 KM

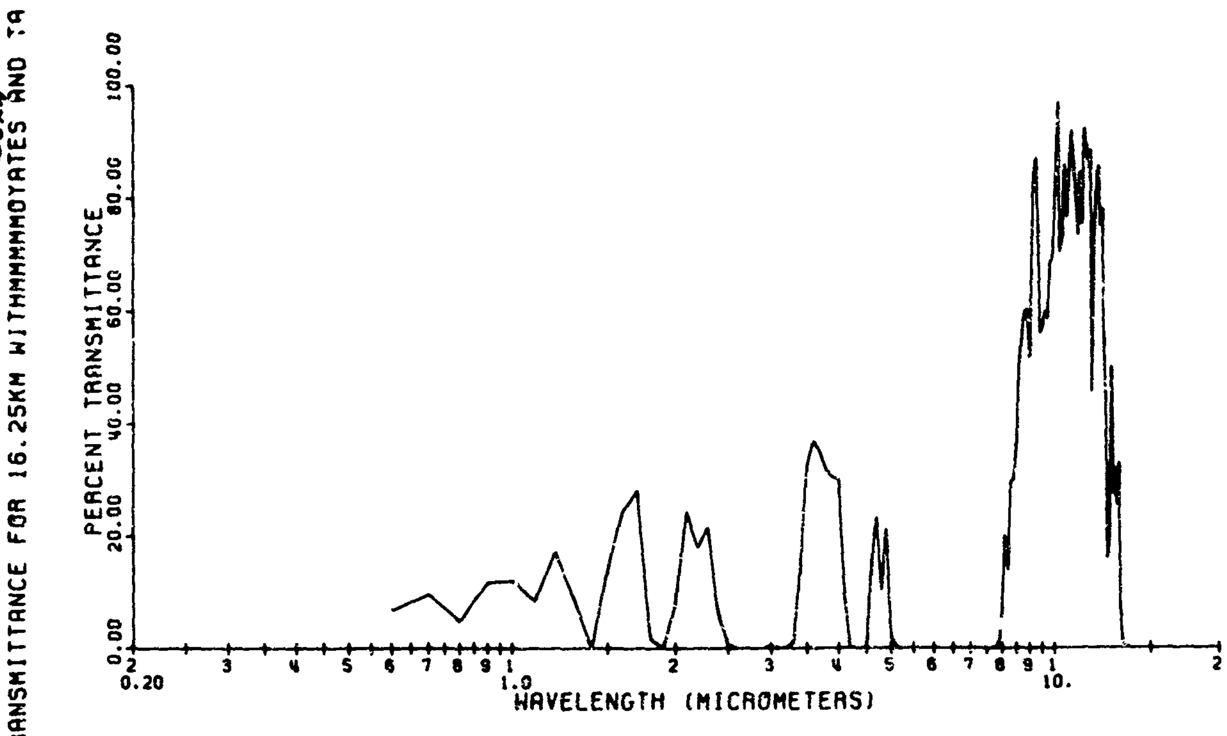


Figure 26. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 16.25 KM

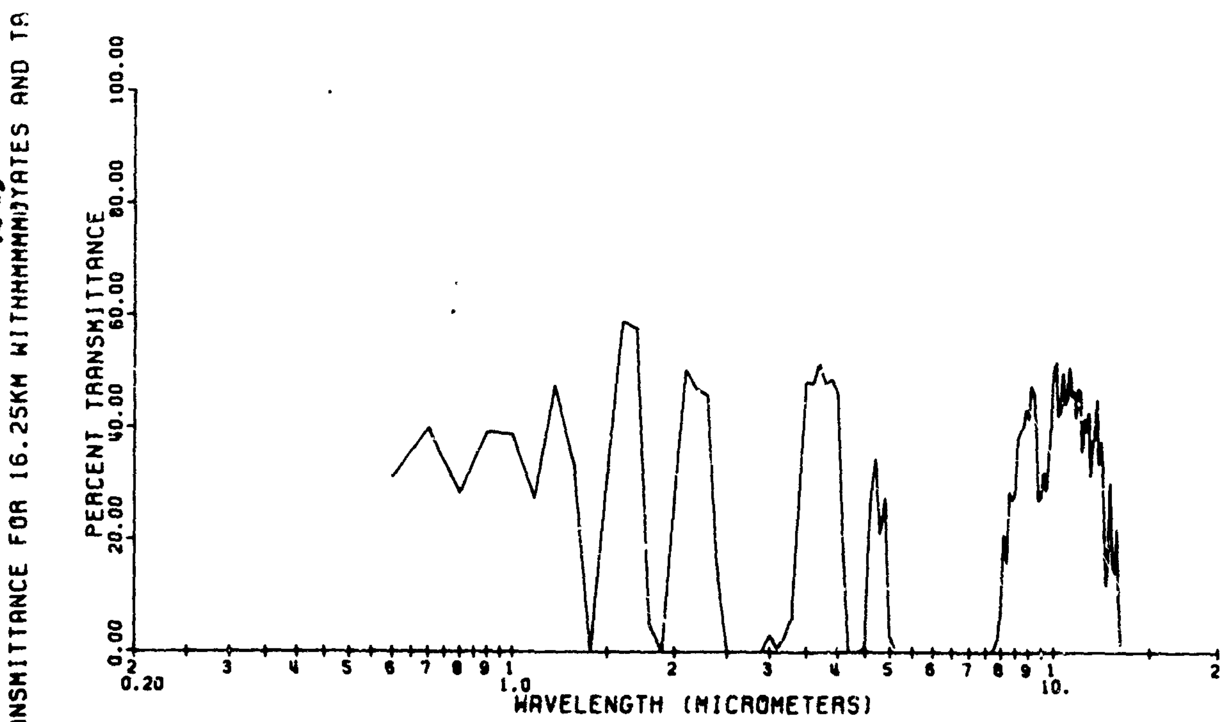


Figure 27. Yates & Taylor Data Measured at 16.25 KM

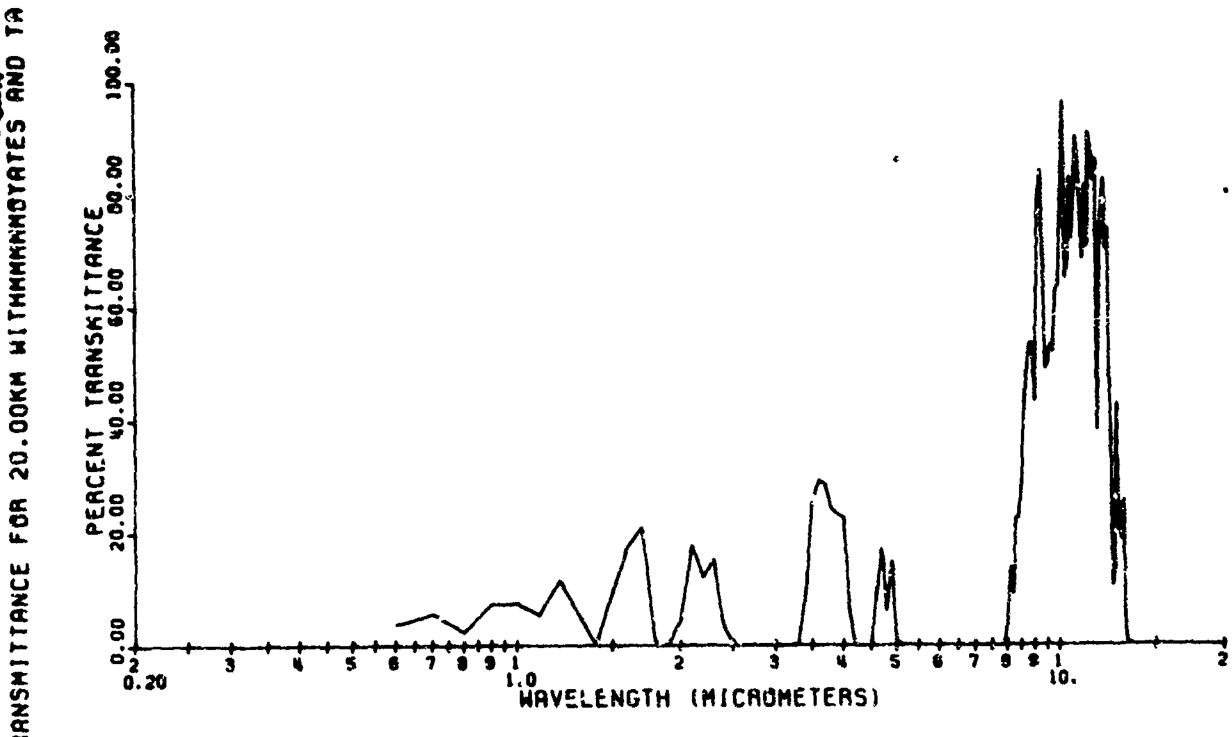


Figure 28. Yates & Taylor Data Measured at 5.5 KM and Interpolated to Range of 20 KM

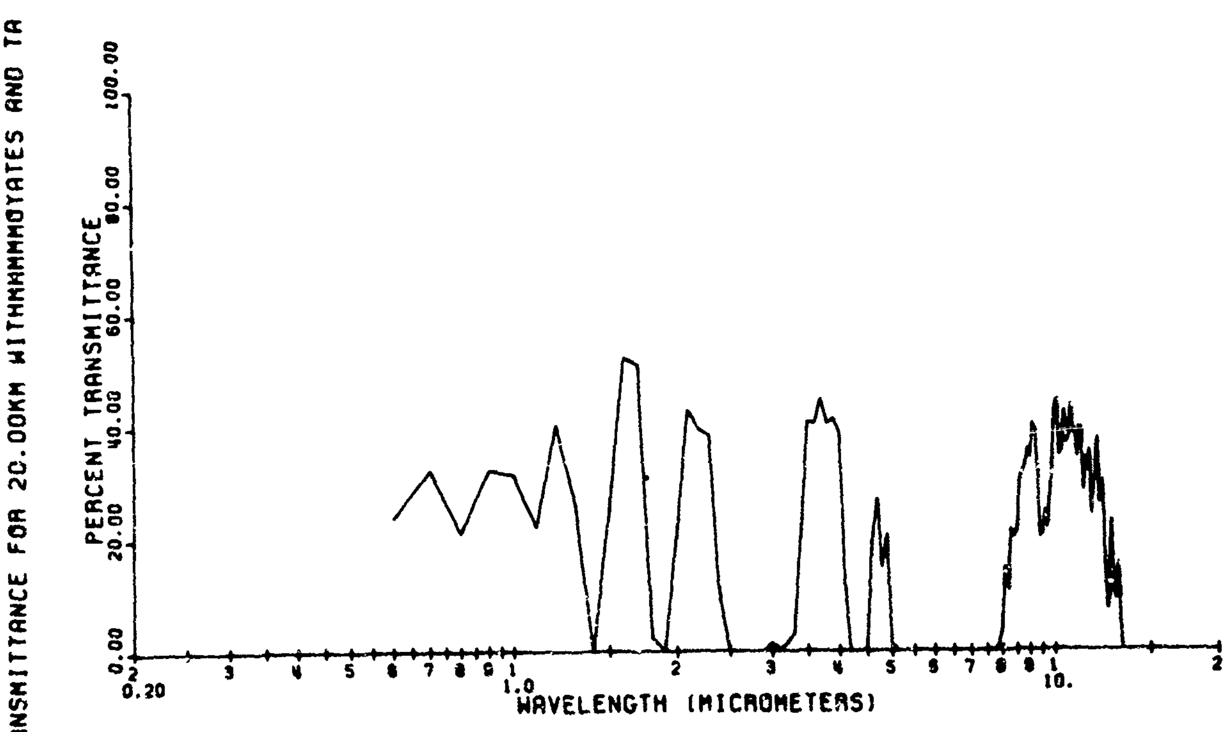


Figure 29. Yates & Taylor Data Measured at 16.25 KM and Interpolated to Range 20 KM

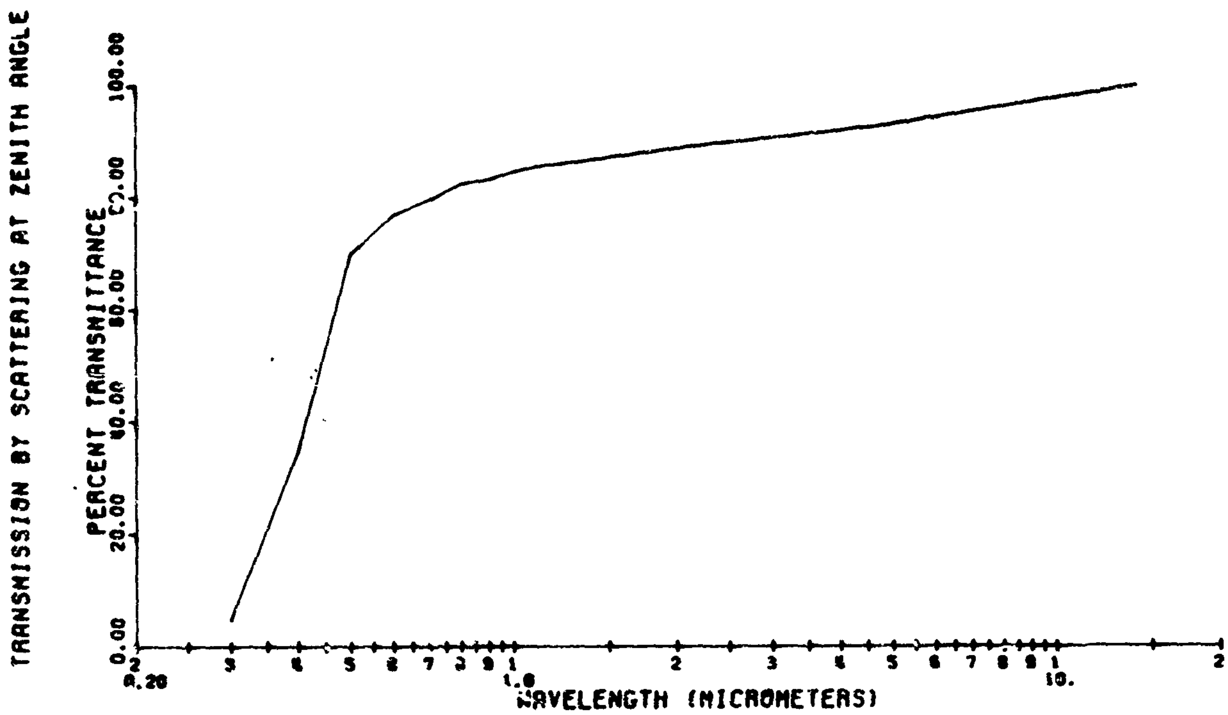


Figure 32. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 1, Zenith Angle of 18.1°

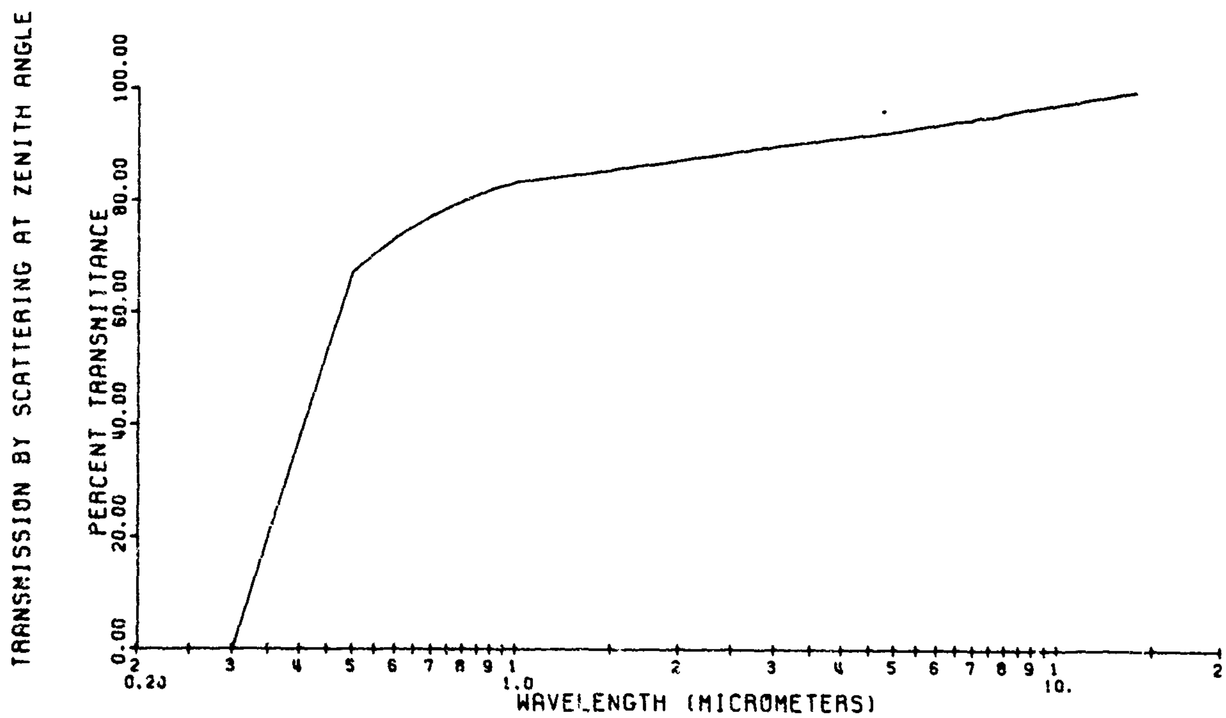


Figure 33. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 2. Zenith Angle of 31.7°

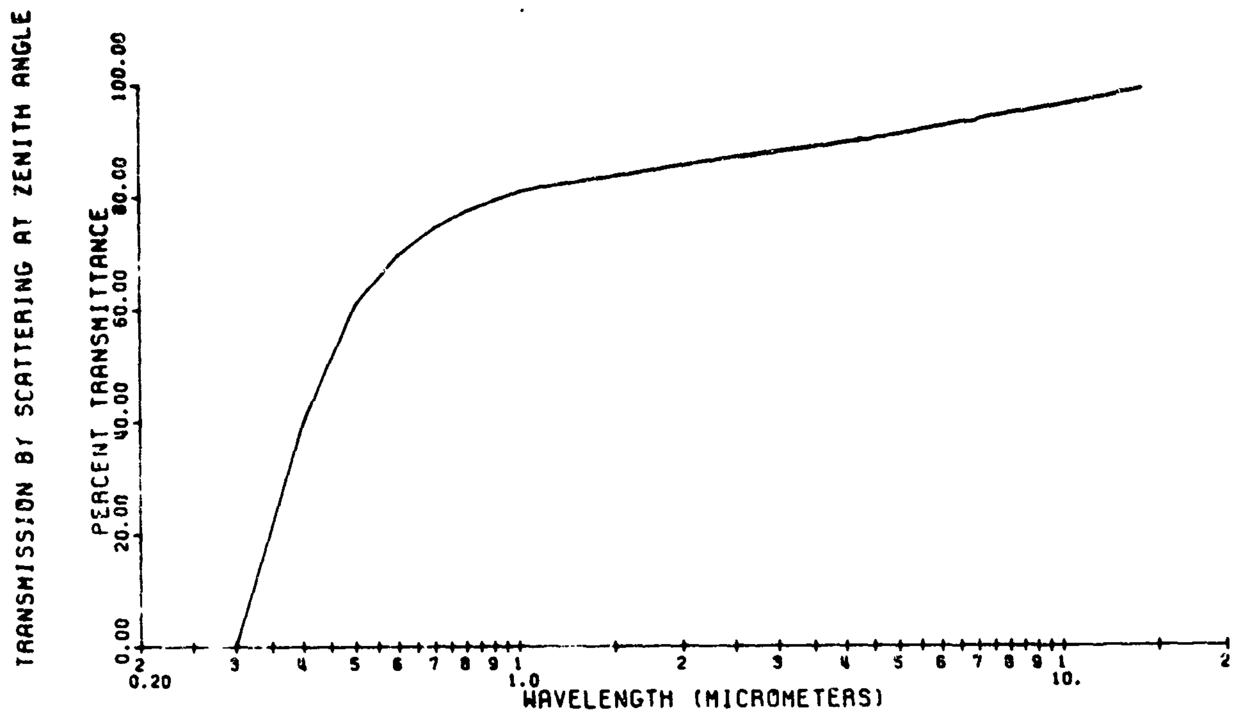


Figure 34. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 3, Zenith Angle of 41.4°

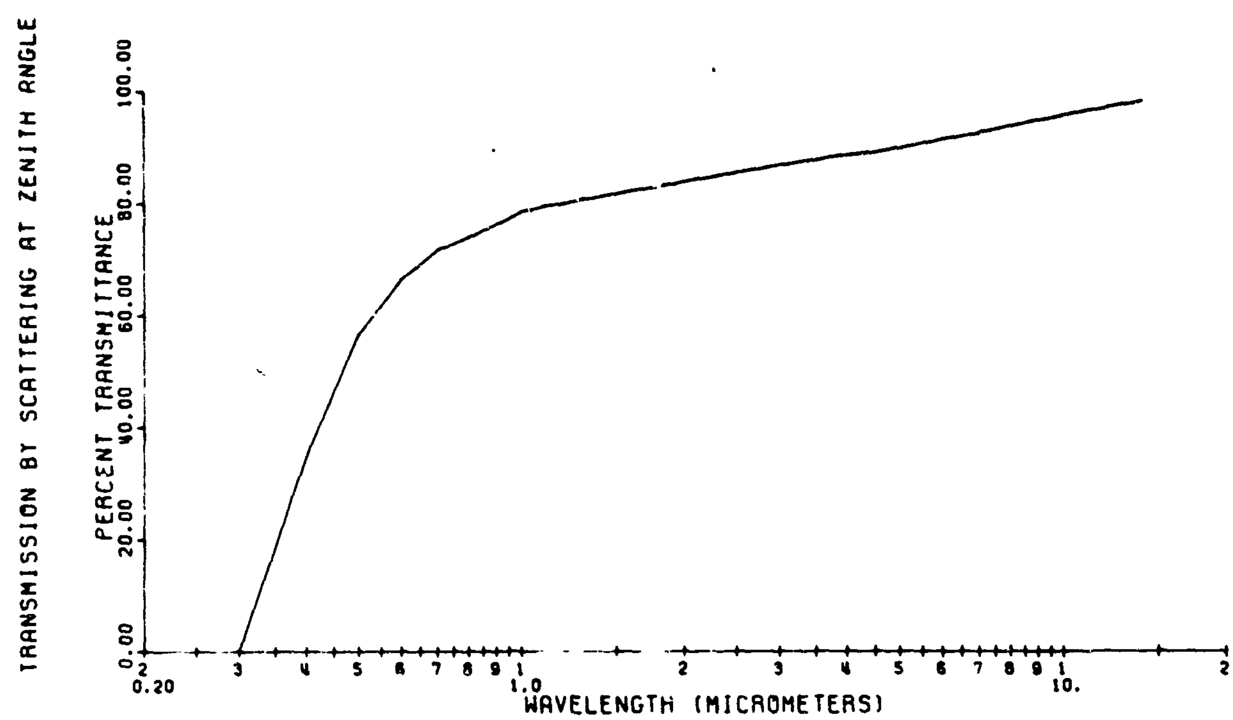


Figure 35. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 4, Zenith Angle of 49.5°

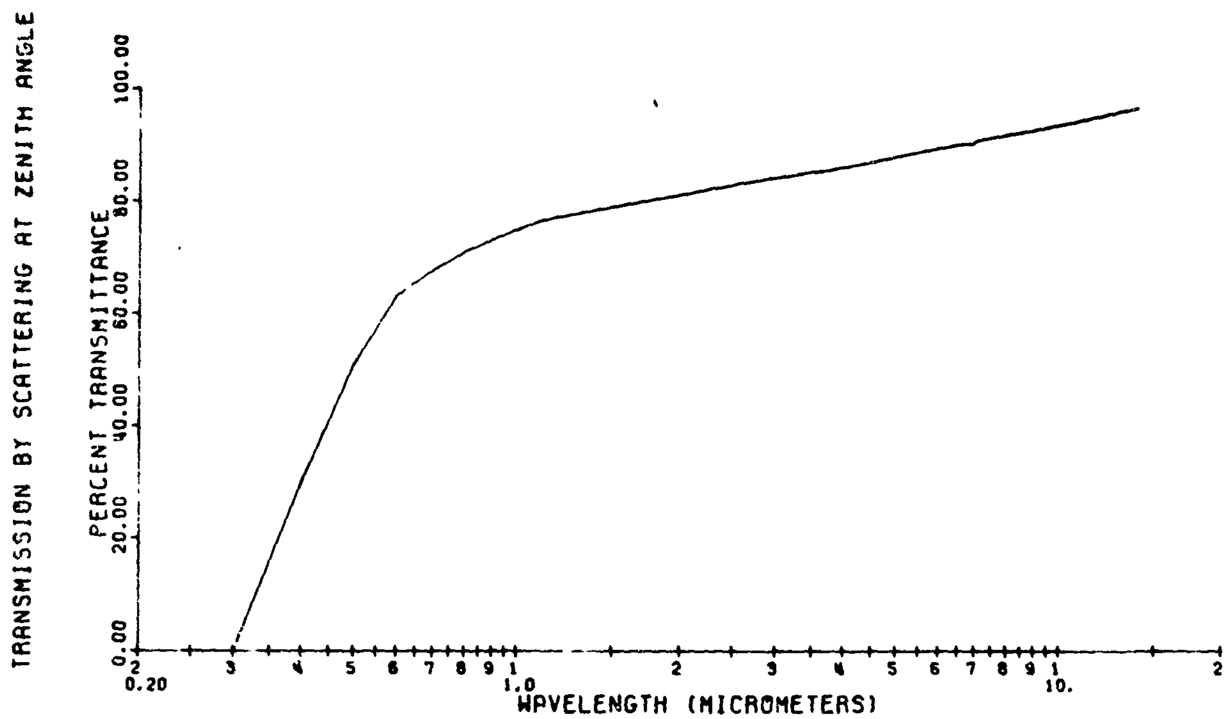


Figure 36. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 5, Zenith Angle of 56.6°

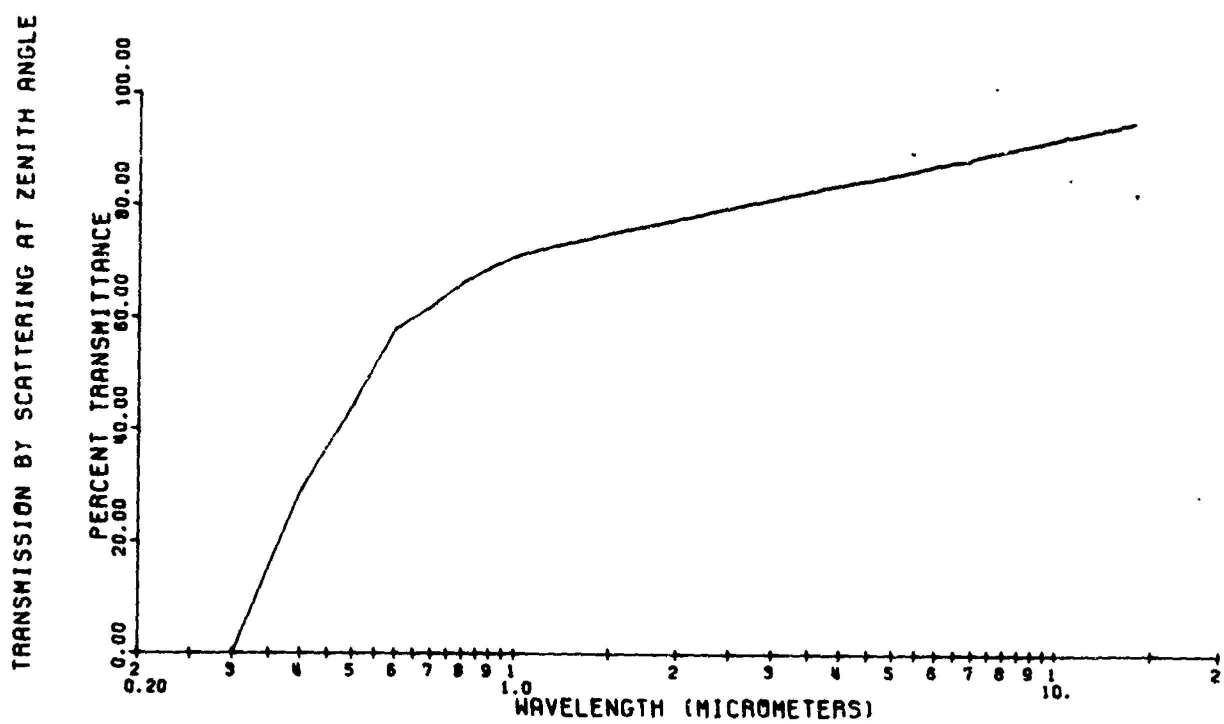


Figure 37. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 6, Zenith Angle of 63.2°

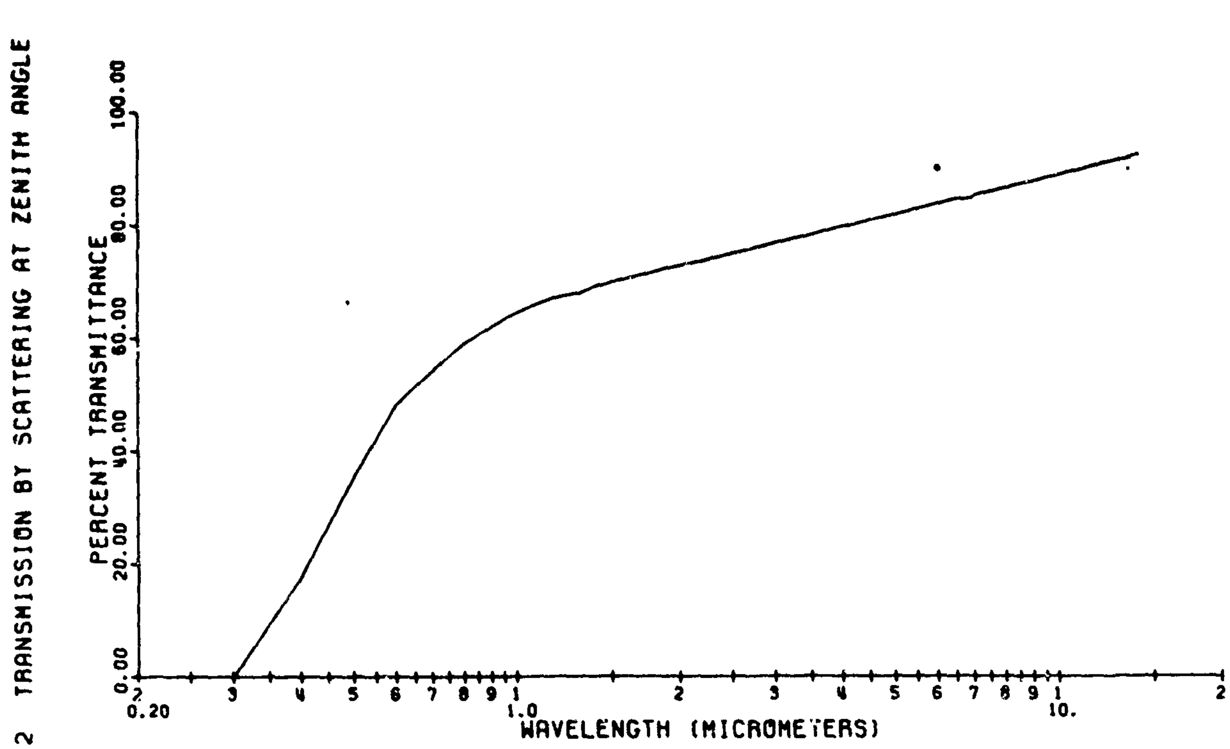


Figure 38. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 7, Zenith Angle of 69.5° (U)

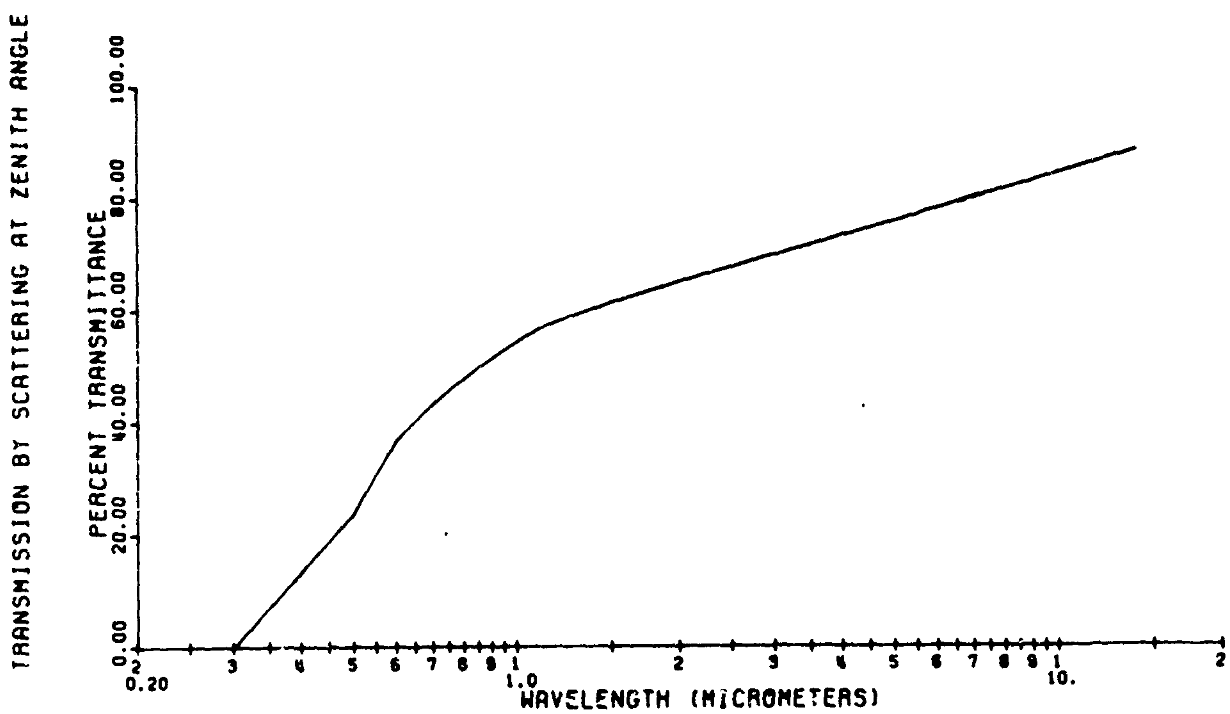


Figure 39. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 8, Zenith Angle of 75.5° (U)

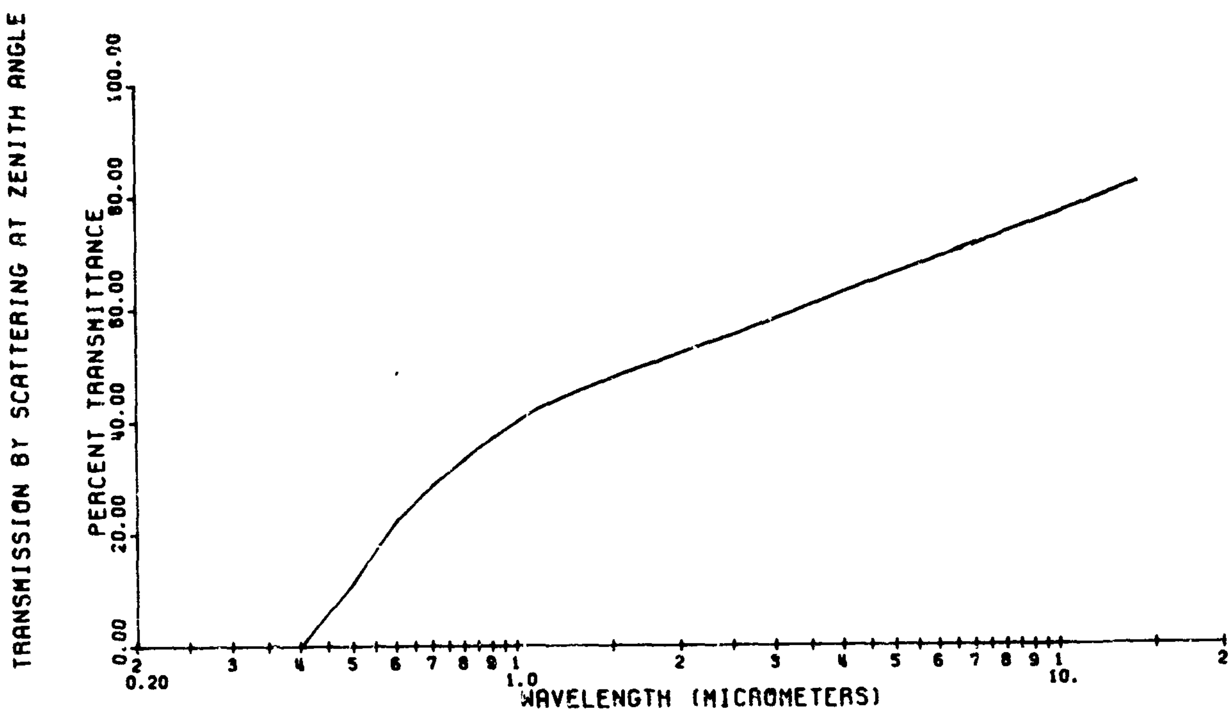


Figure 40. Transmittance Component Caused by Part' :le Scattering and Ozone (Elterman Method) for Sky Segment 9, Zenith Angle of 81.4°

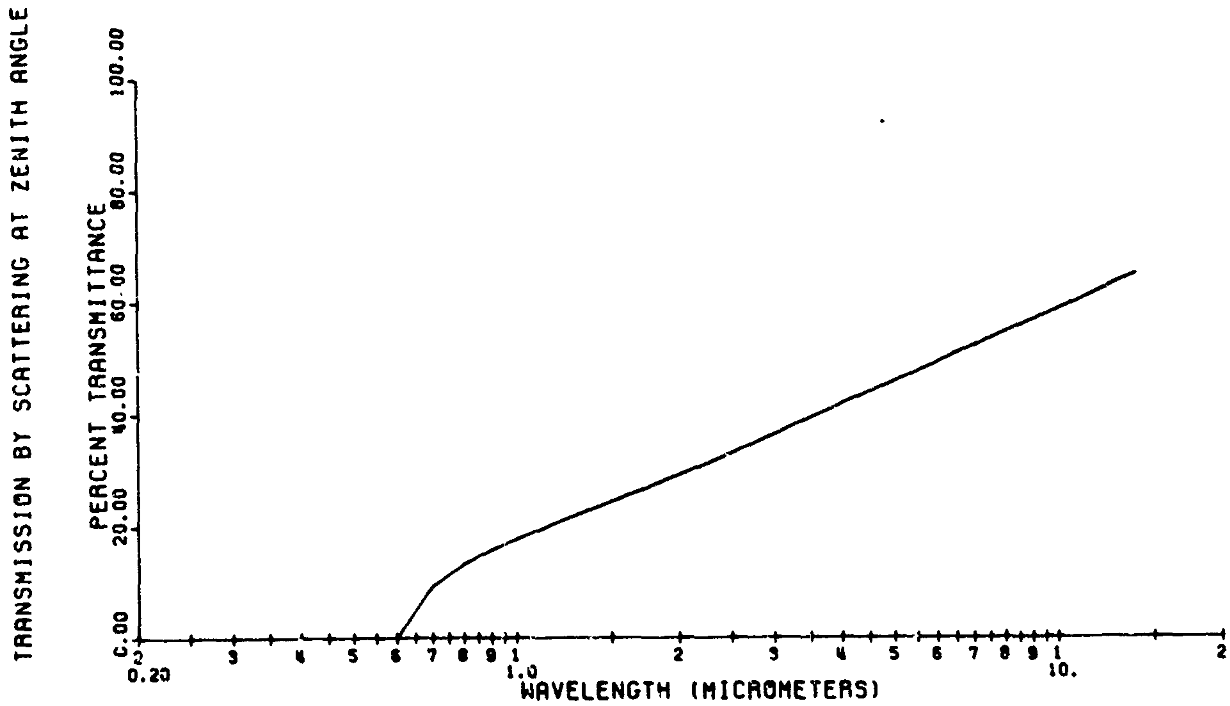


Figure 41. Transmittance Component Caused by Particle Scattering and Ozone (Elterman Method) for Sky Segment 10, Zenith Angle of 87.2°

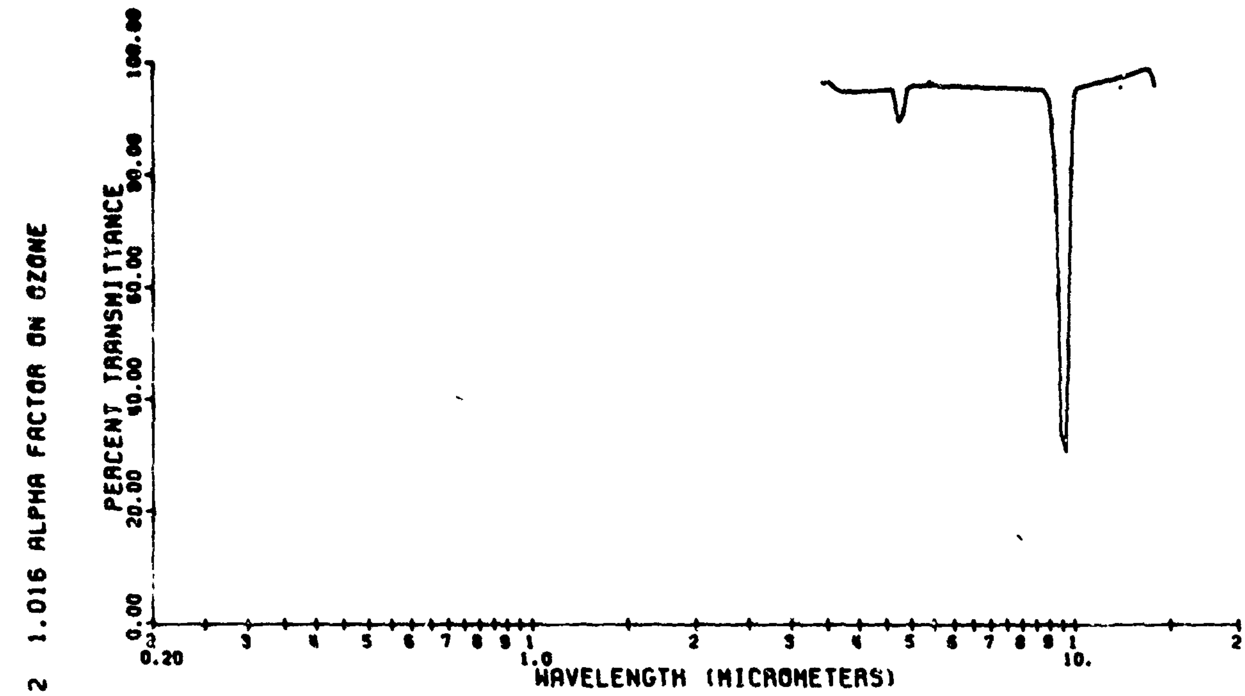


Figure 43. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 1, Zenith Angle of 18.1°

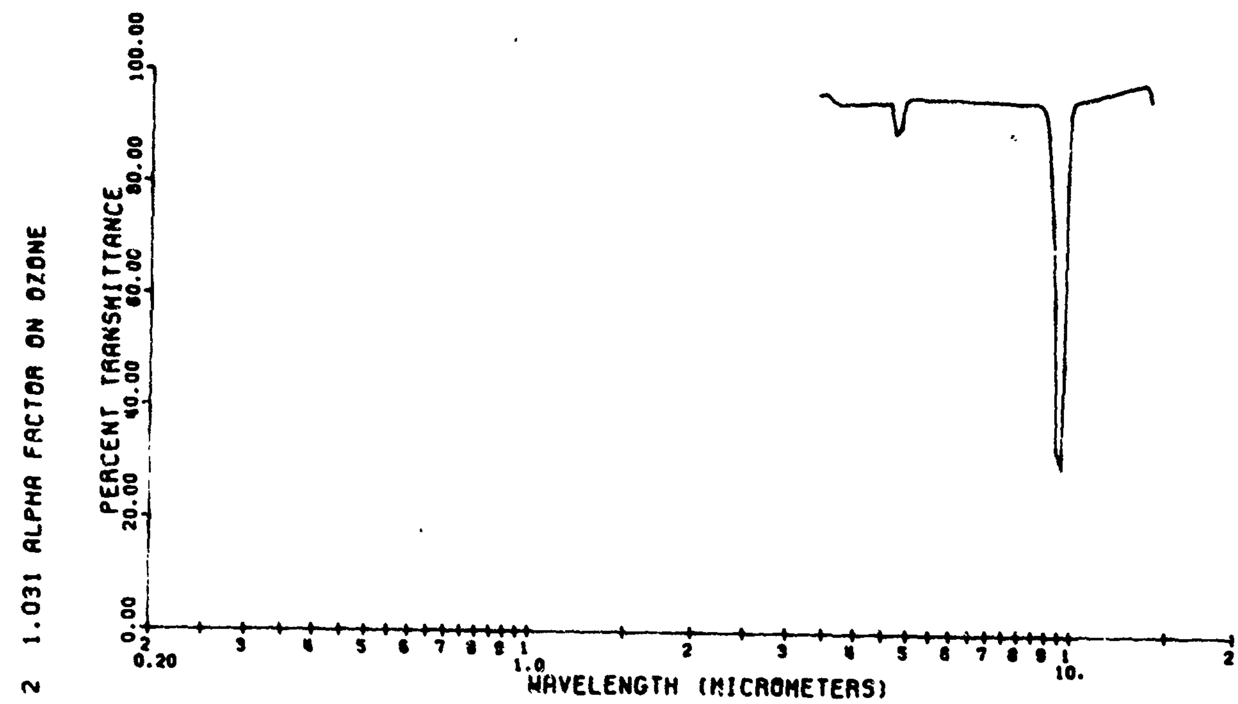


Figure 44. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 2, Zenith Angle of 31.7°

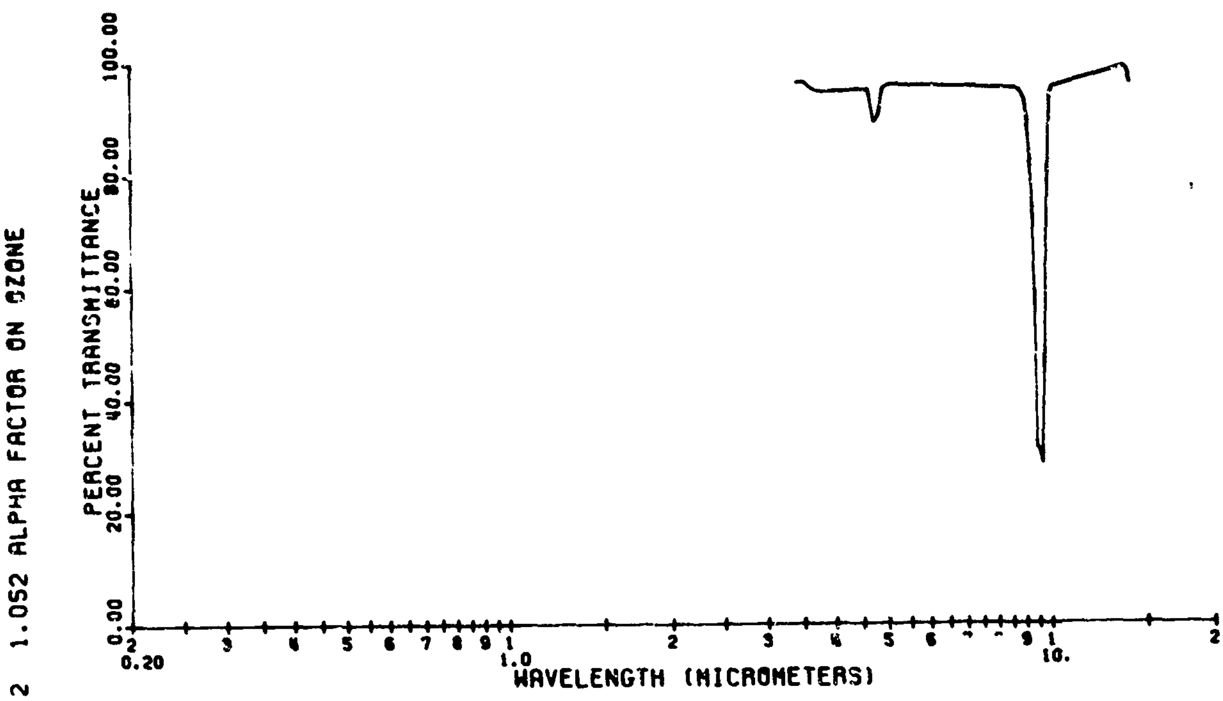


Figure 45. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 3, Zenith Angle of 41.4°

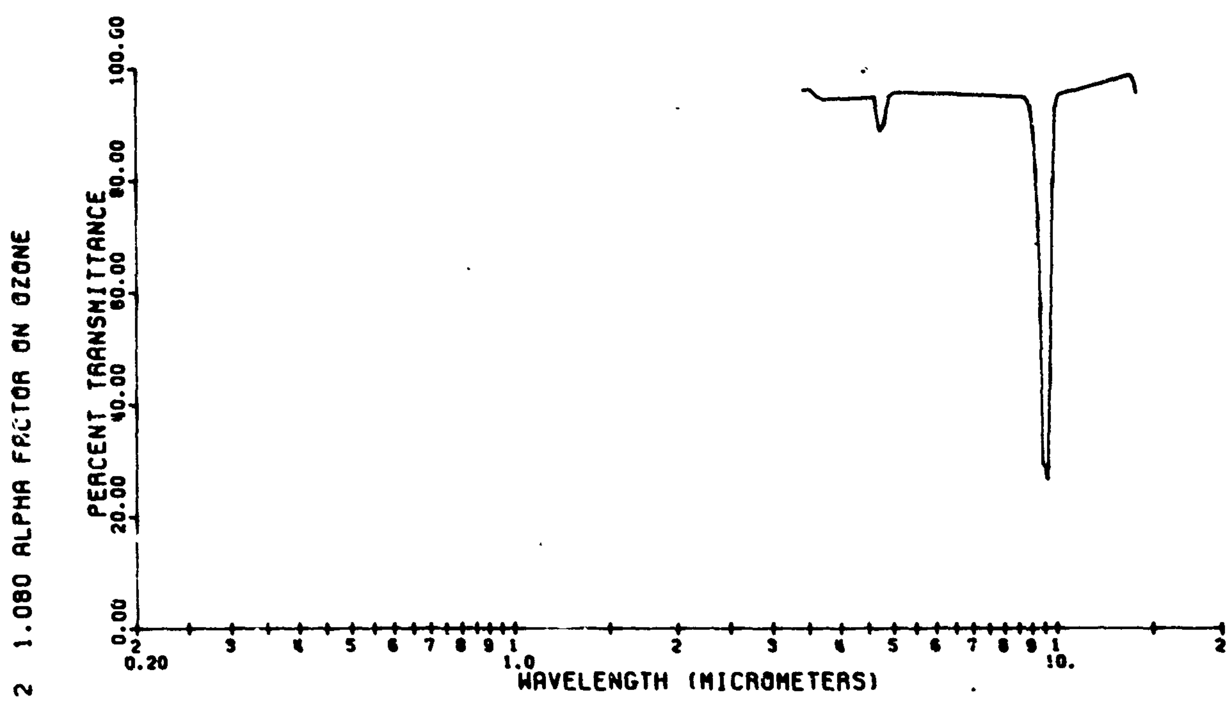


Figure 46. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 4, Zenith Angle of 49.5°

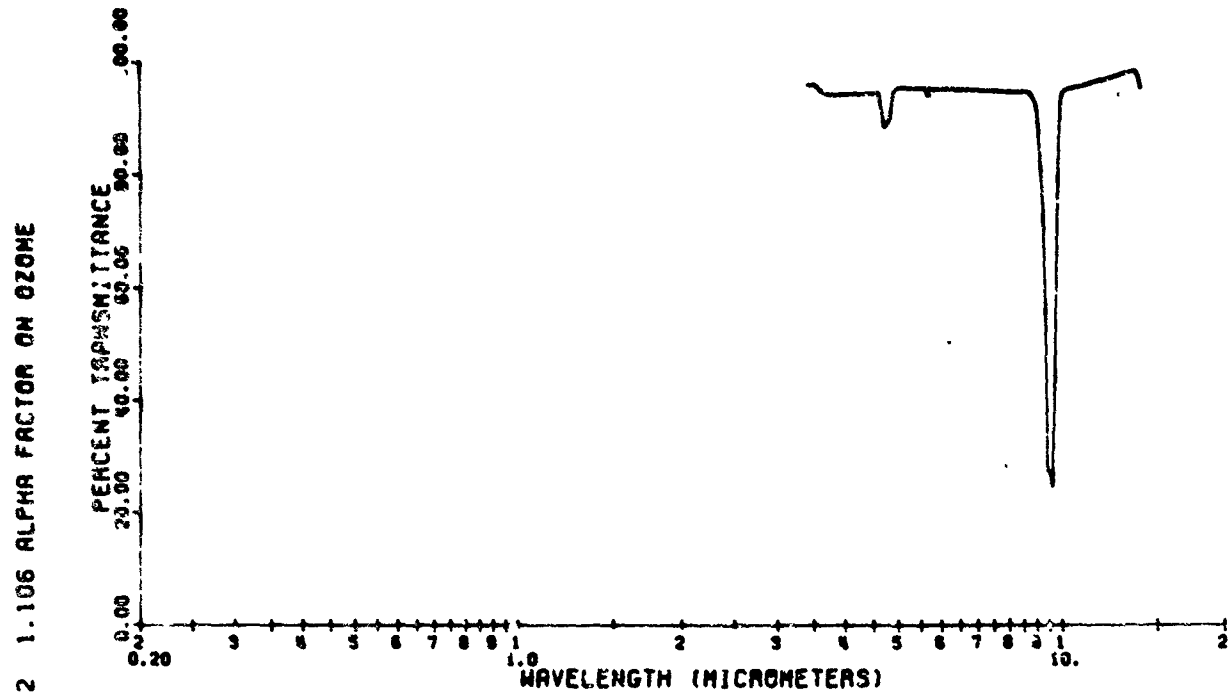


Figure 47. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 5, Zenith Angle of 56.6°

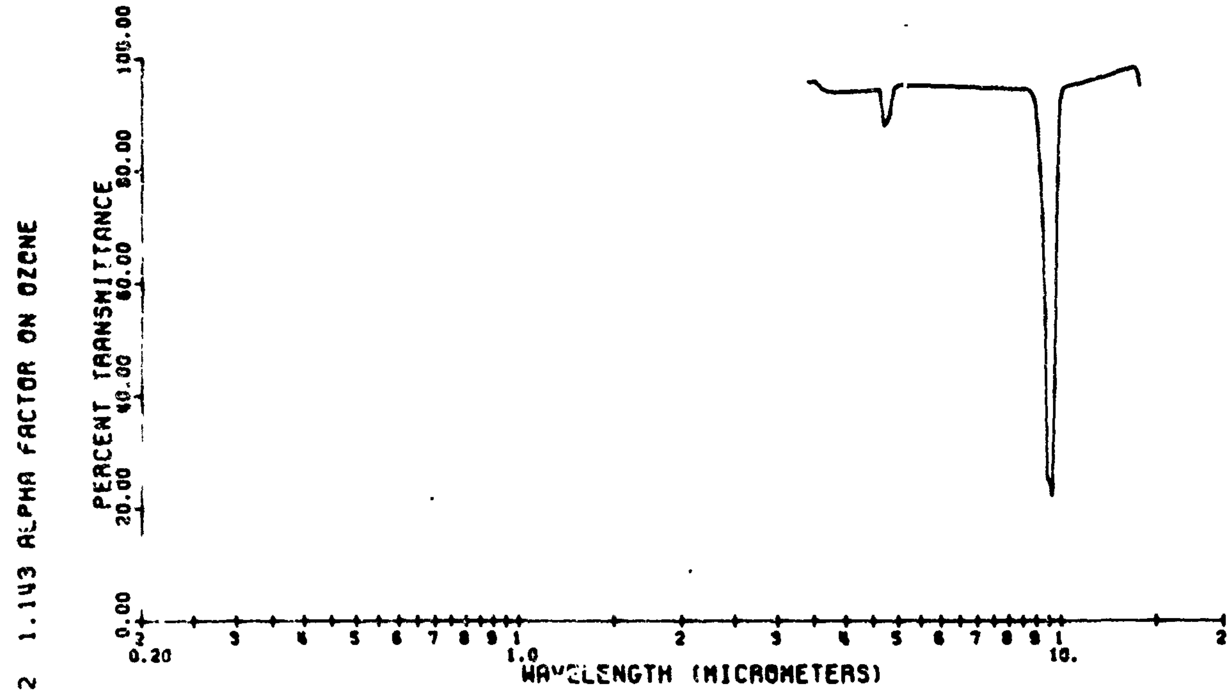


Figure 48. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 6, Zenith Angle of 63.2°

2 1.185 ALPHA FACTOR ON OZONE

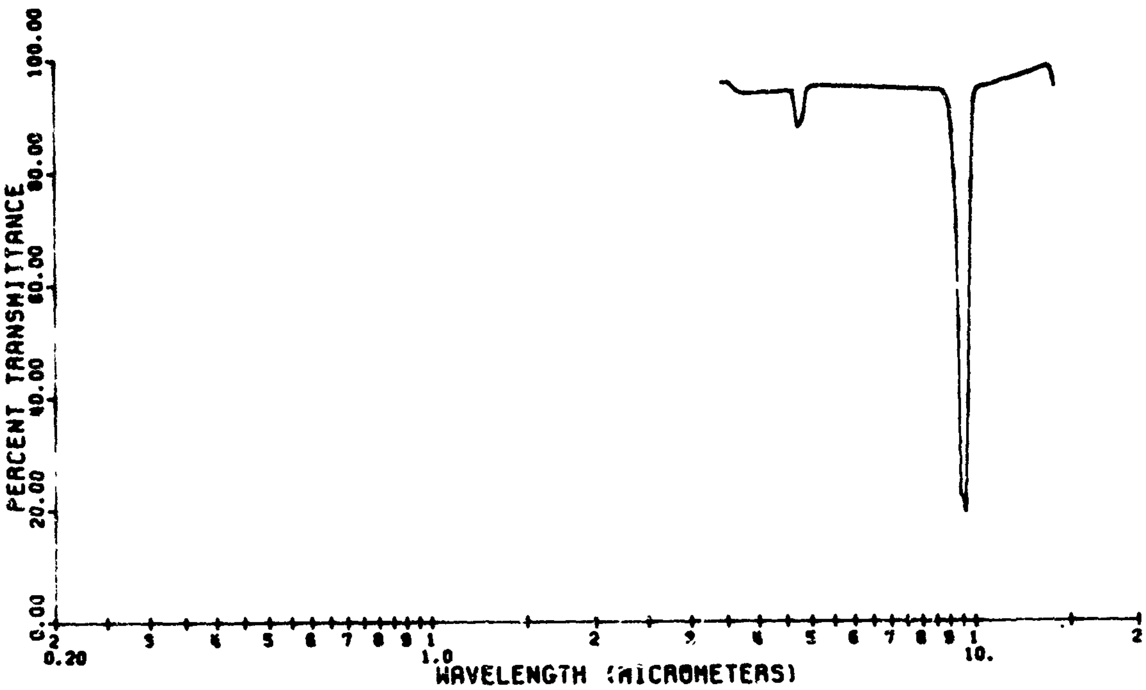


Figure 49. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 7, Zenith Angle of 69.5°

2 1.242 ALPHA FACTOR ON OZONE

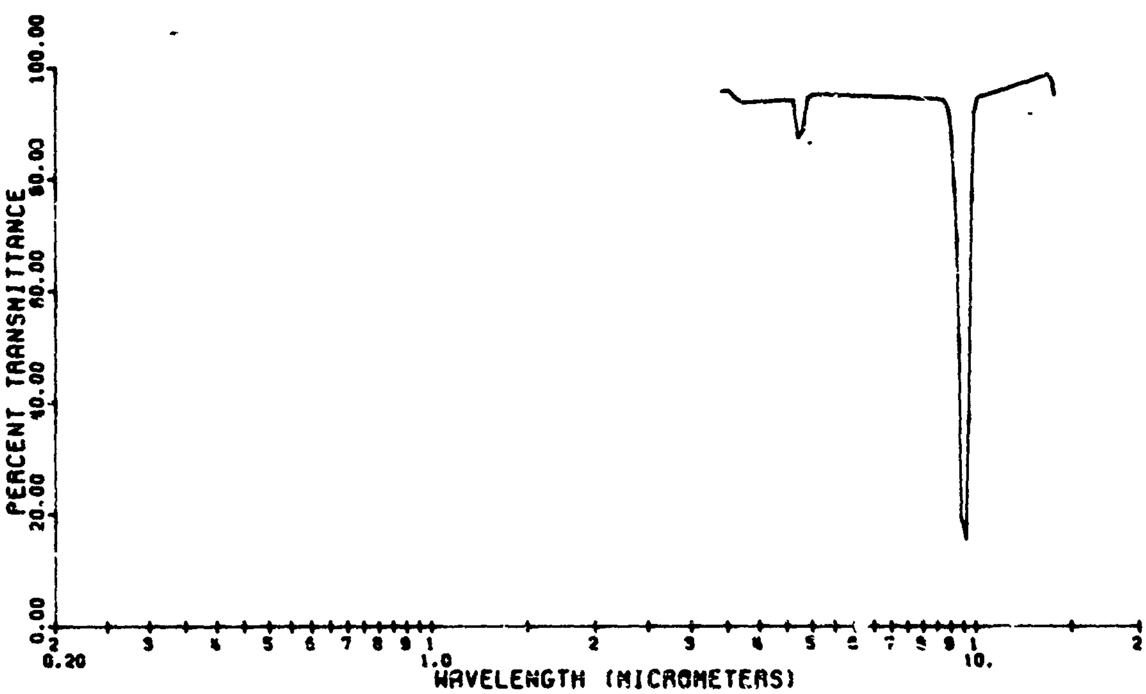


Figure 50. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 8, Zenith Angle of 75.5°

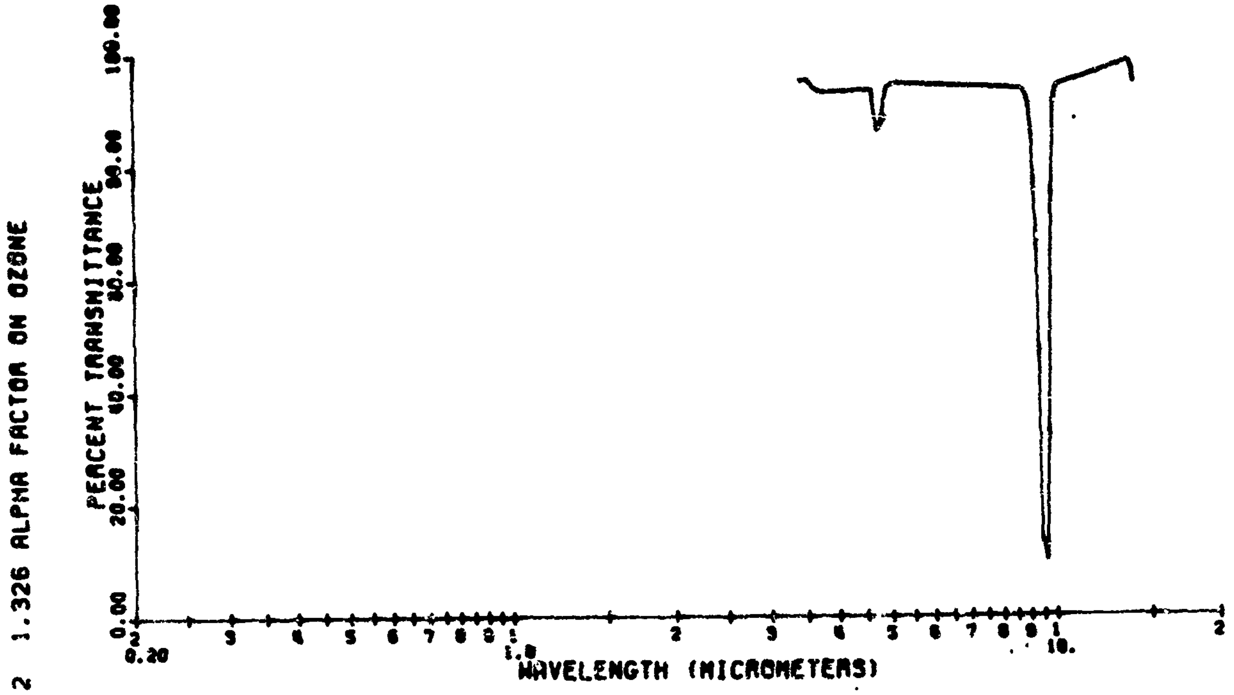


Figure 51. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 9, Zenith Angle of 81.4°

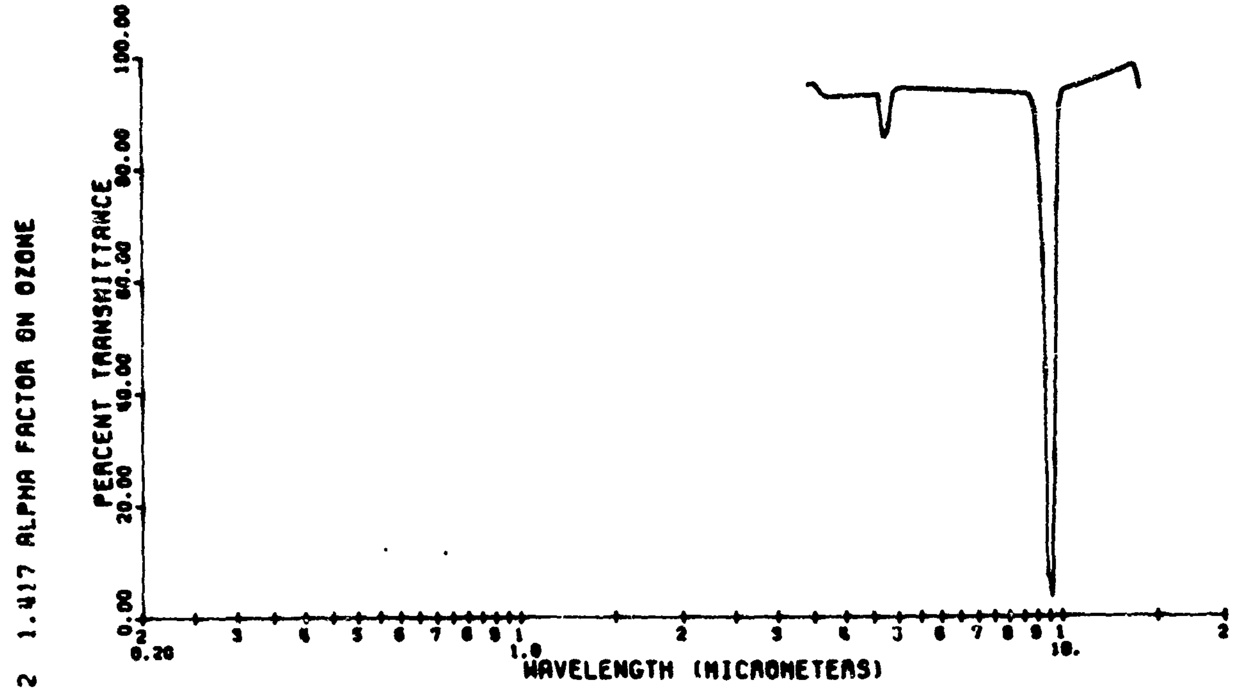


Figure 52. Transmittance Component Caused by Ozone (3.4-14 μm) for Sky Segment 10, Zenith Angle of 87.2°

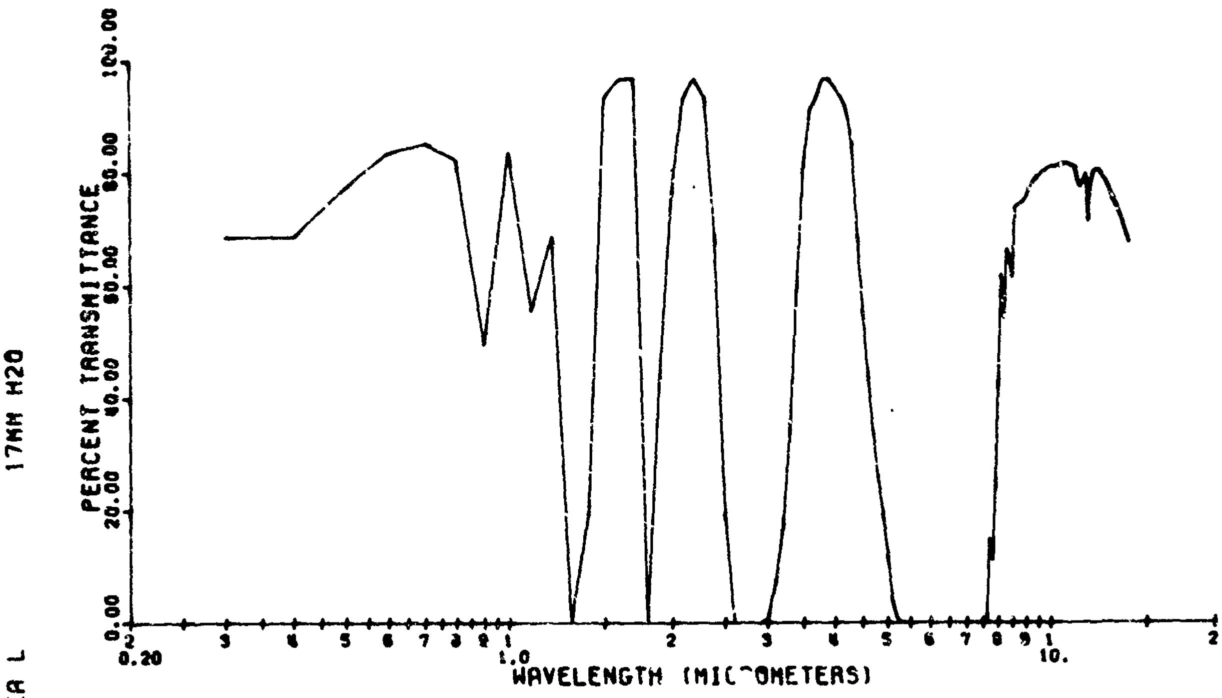


Figure 54. Transmittance Component Caused by Water Vapor for Sky Segment 1, Zenith Angle of 18.1°

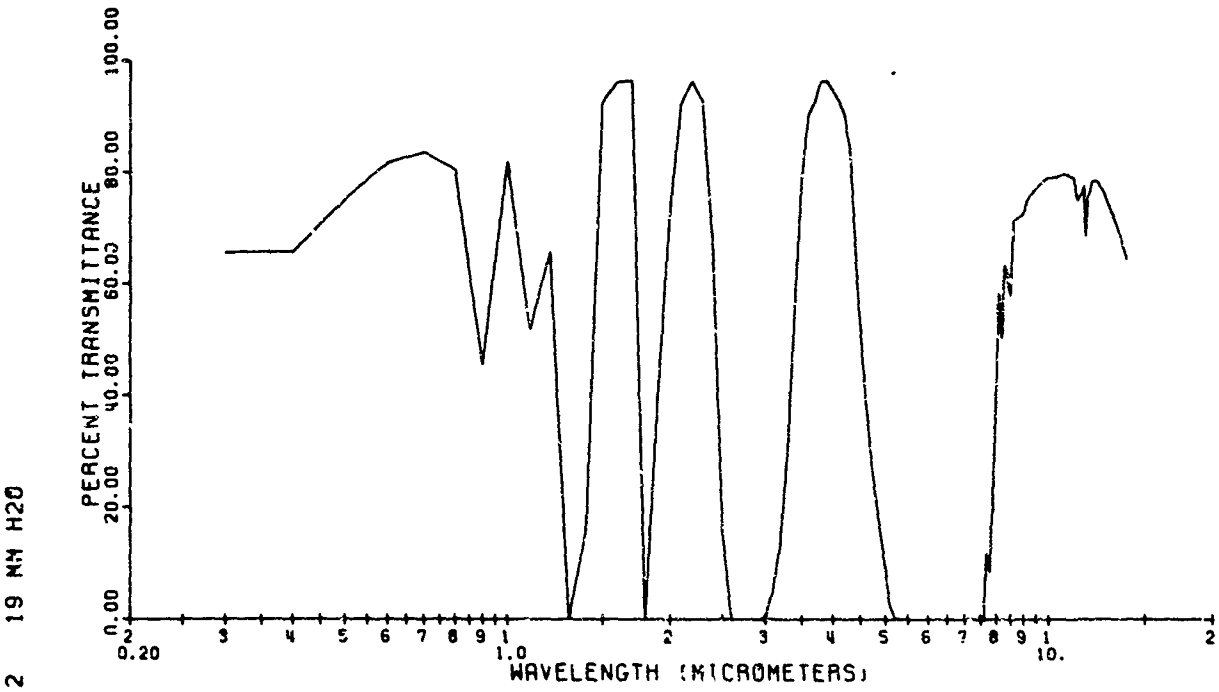


Figure 55. Transmittance Component Caused by Water Vapor for Sky Segment 2, Zenith Angle of 31.7°

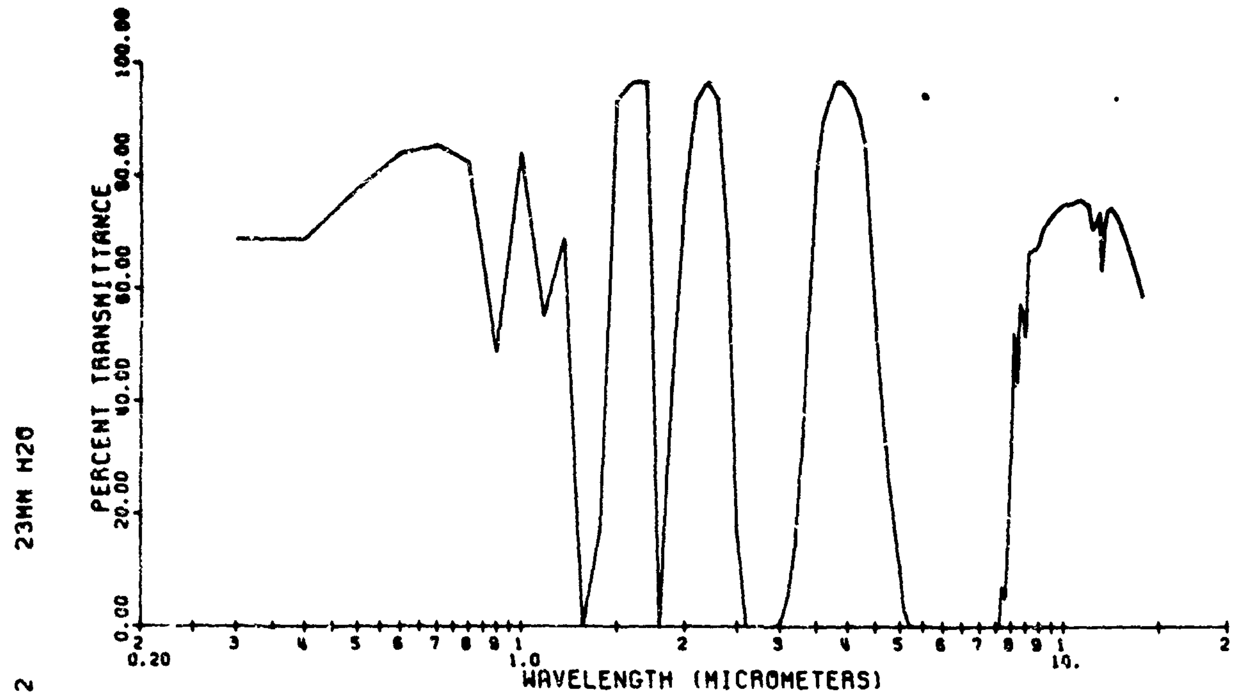


Figure 56. Transmittance Component Caused by Water Vapor for Sky Segment 3, Zenith Angle of 41.4°

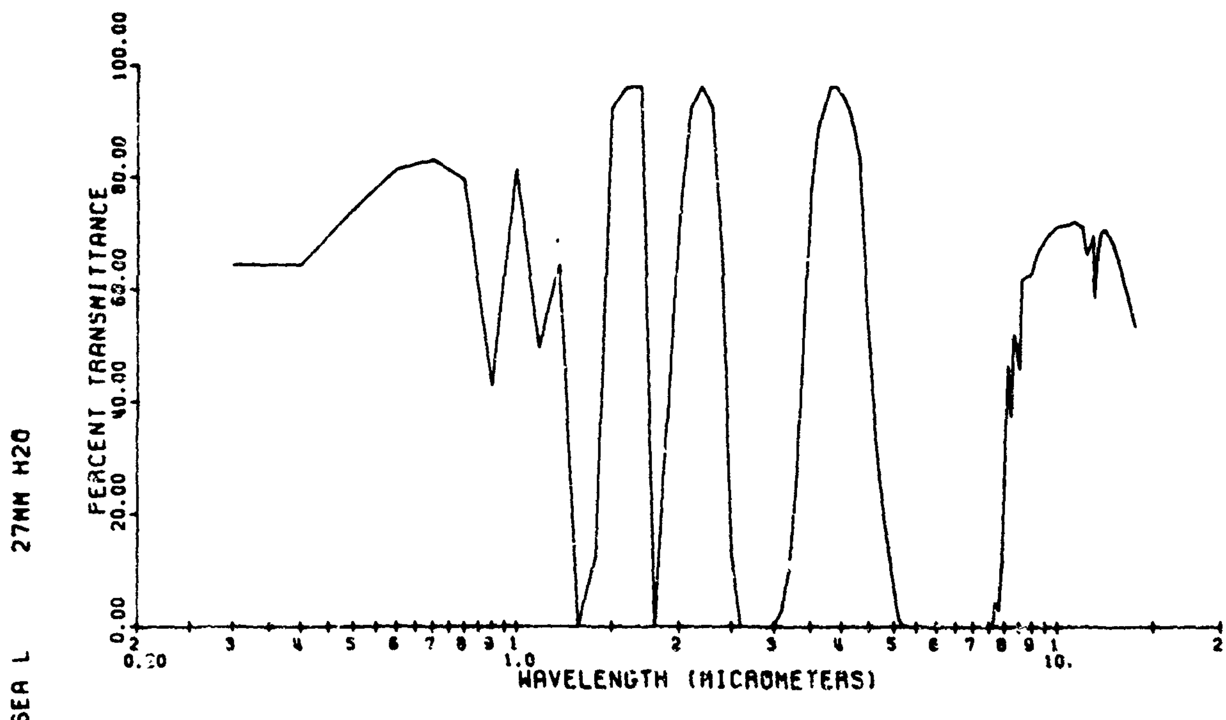


Figure 57. Transmittance Component Caused by Water Vapor for Sky Segment 4, Zenith Angle of 49.5°

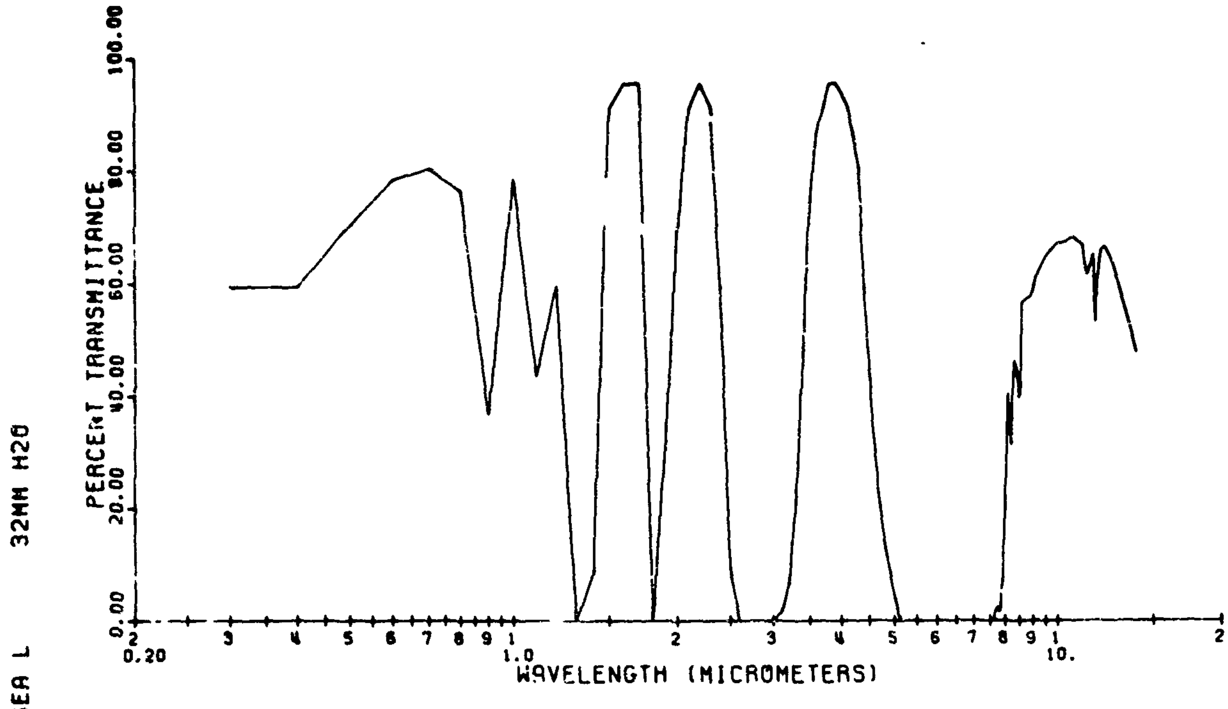


Figure 58. Transmittance Component Caused by Water Vapor for Sky Segment 5, Zenith Angle of 56.6°

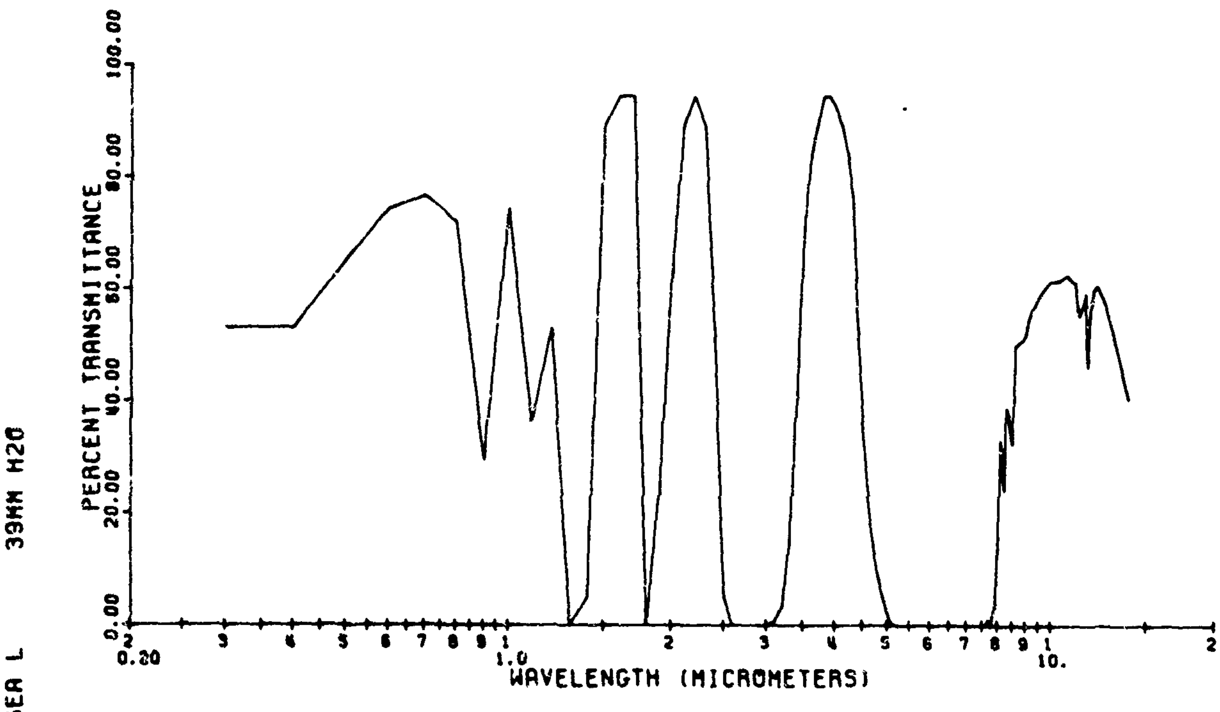


Figure 59. Transmittance Component Caused by Water Vapor for Sky Segment 6, Zenith Angle of 63.2°

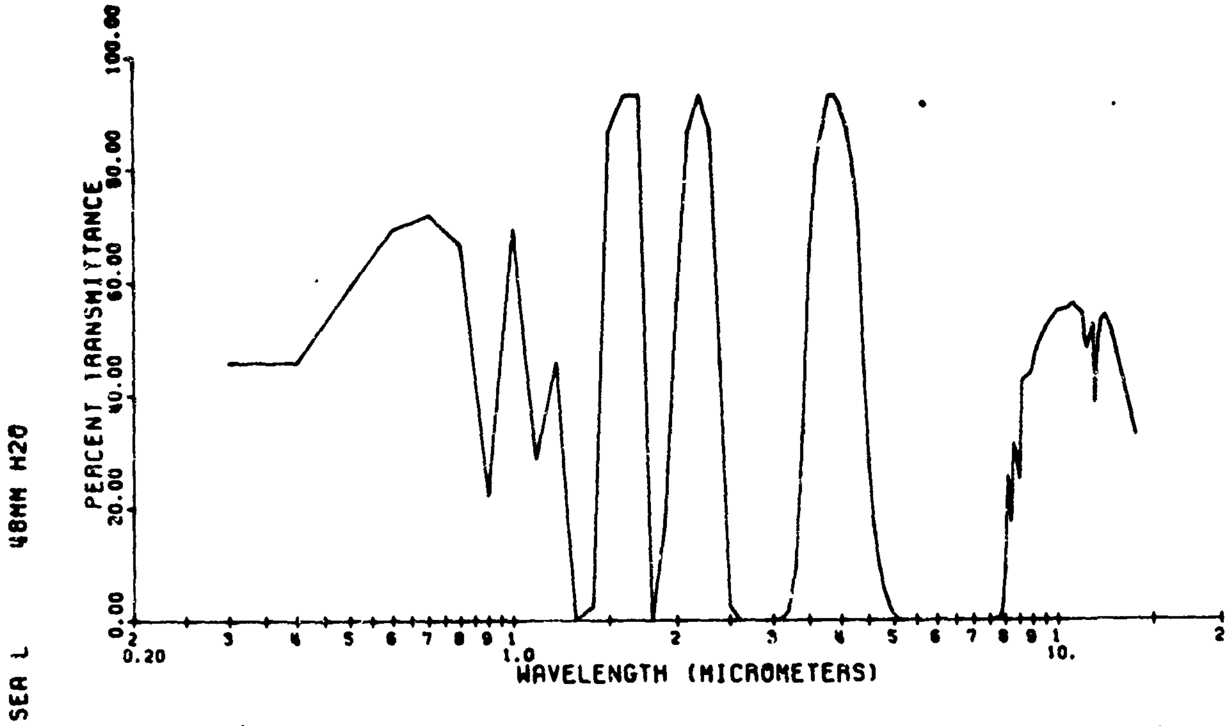


Figure 60. Transmittance Component Caused by Water Vapor for Sky Segment 7, Zenith Angle of 69.5°

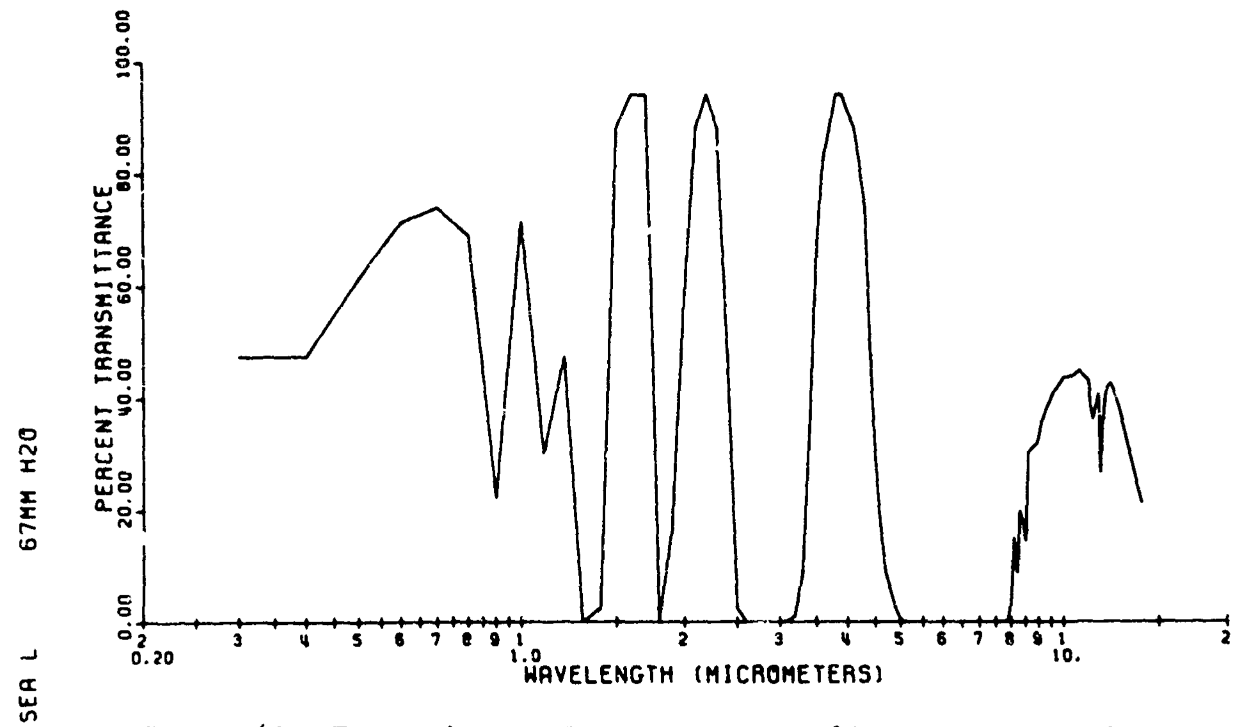


Figure 61. Transmittance Component Caused by Water Vapor for Sky Segment 8, Zenith Angle of 75.5°

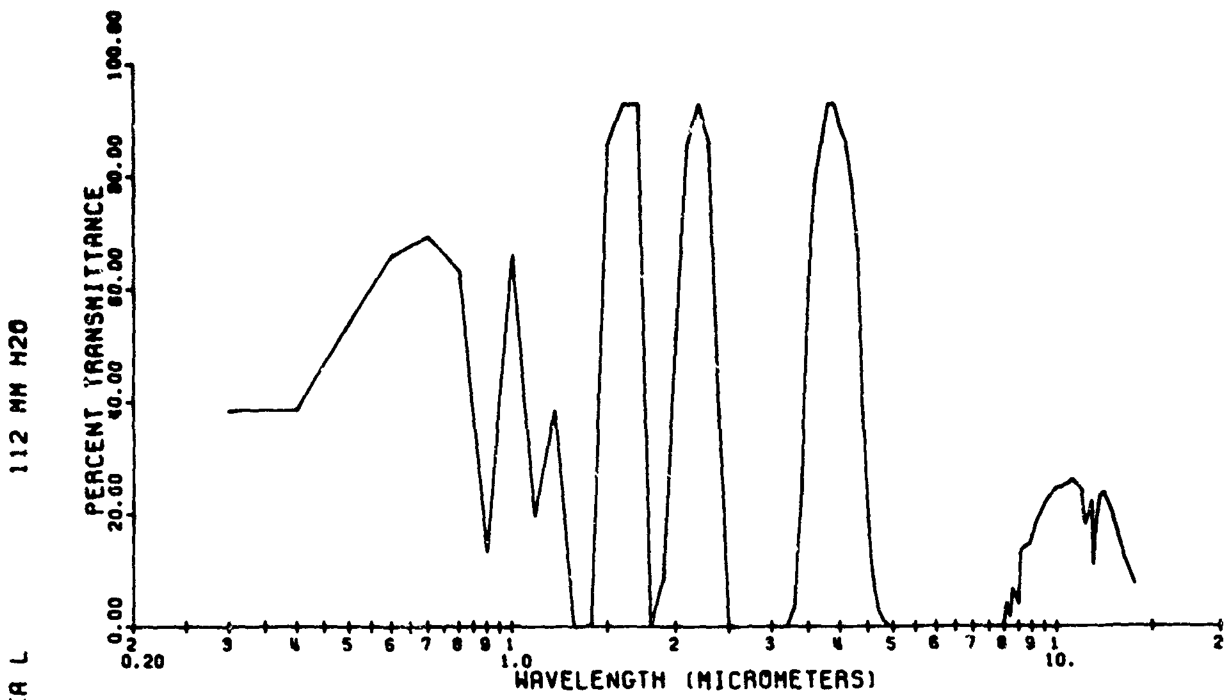


Figure 62. Transmittance Component Caused by Water Vapor for Sky Segment 9, Zenith Angle of 81.4°

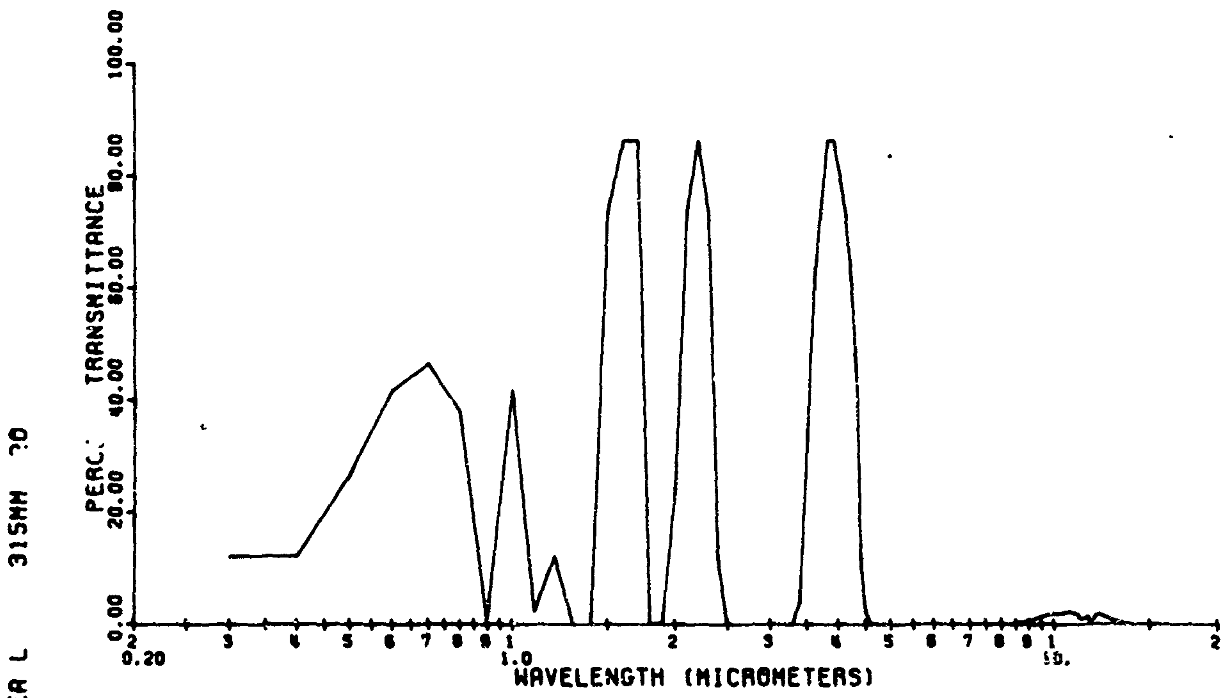


Figure 63. Transmittance Component Caused by Water Vapor for Sky Segment 10, Zenith Angle of 87.2°

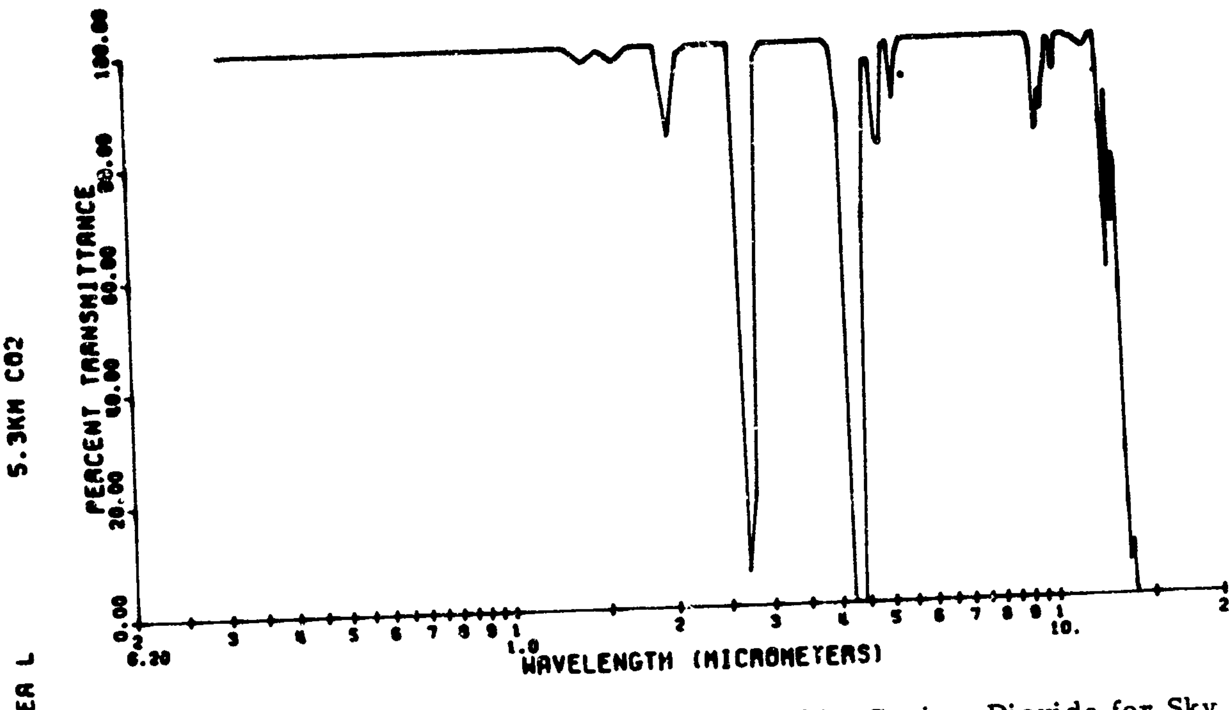


Figure 65. Transmittance Component Caused by Carbon Dioxide for Sky Segment 1, Zenith Angle of 18.1°

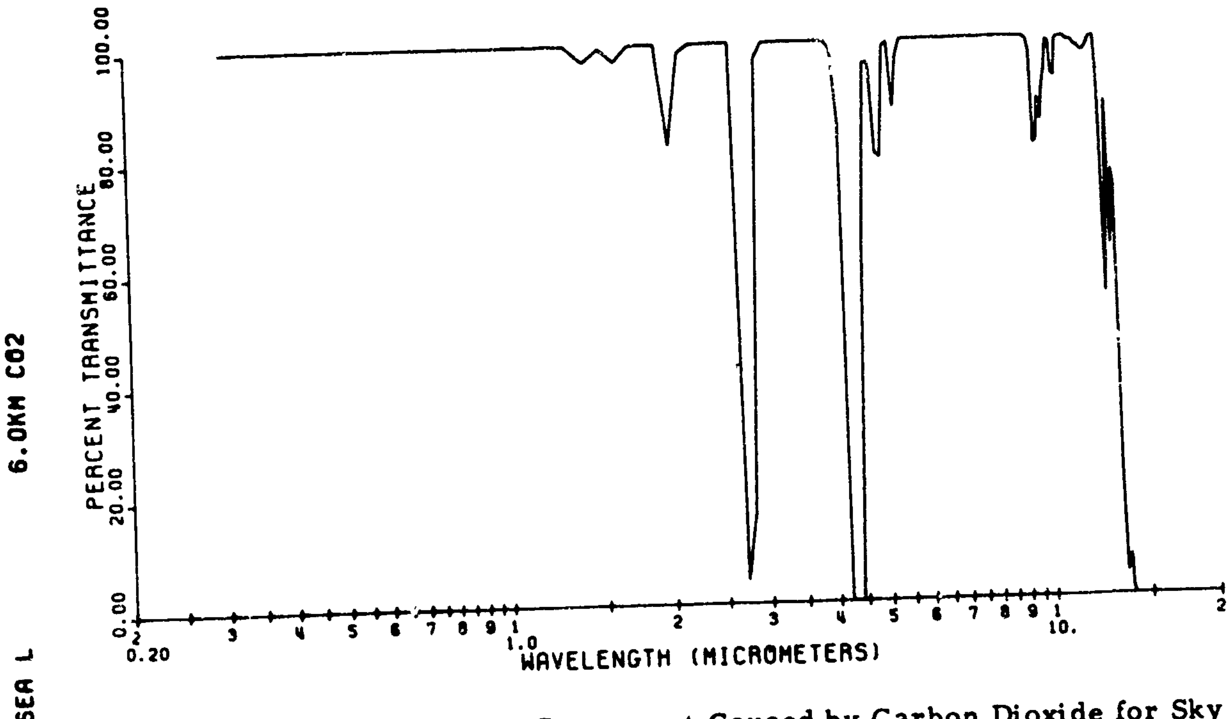


Figure 66. Transmittance Component Caused by Carbon Dioxide for Sky Segment 2, Zenith Angle of 31.7°

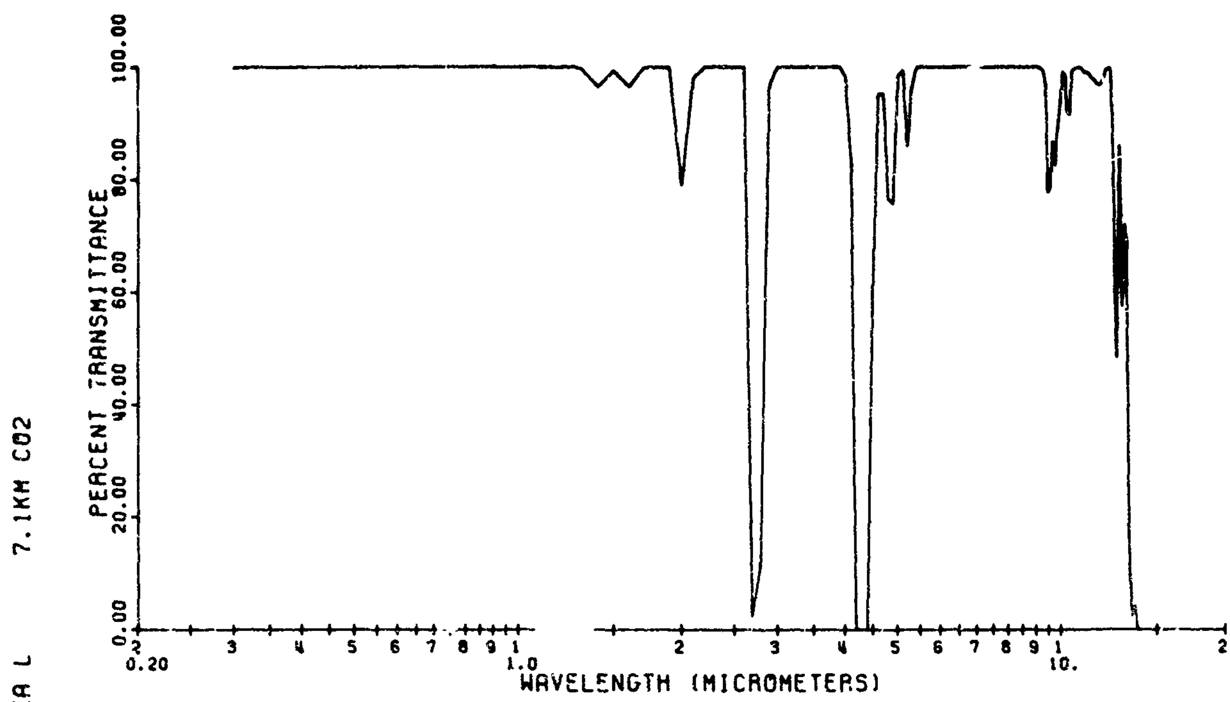


Figure 67. Transmittance Component Caused by Carbon Dioxide for Sky Segment 3, Zenith Angle of 41.4°

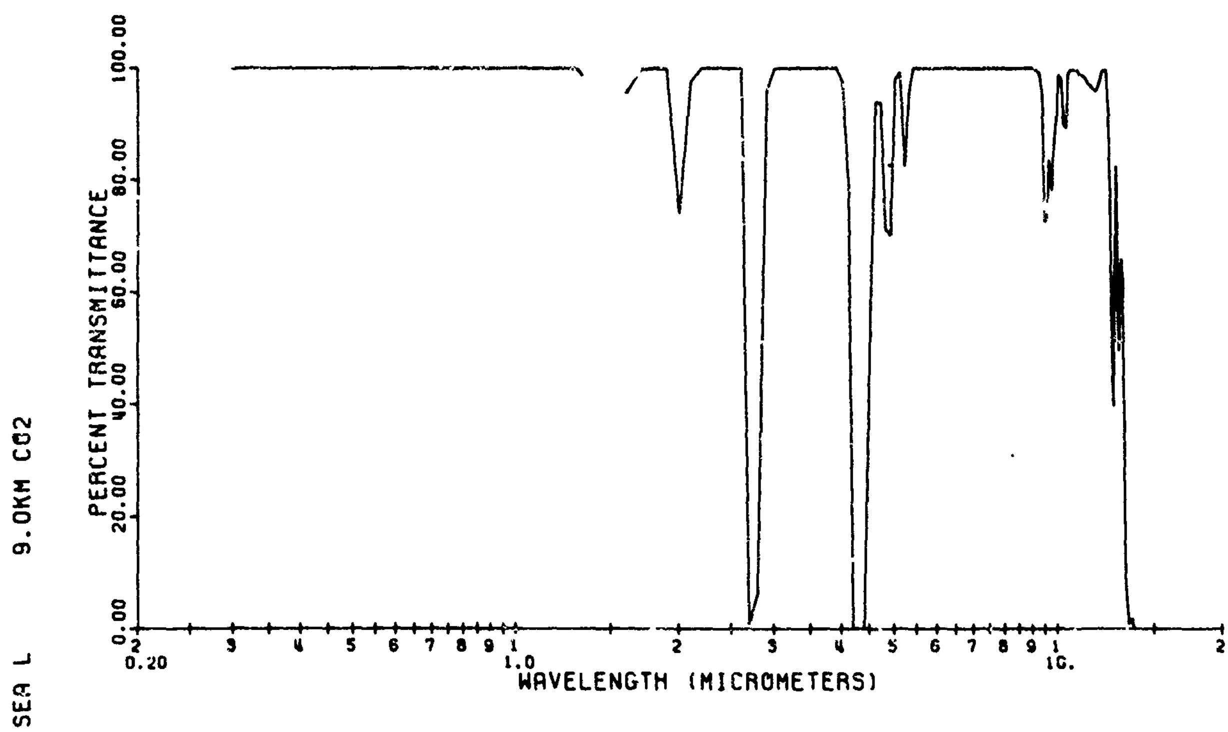


Figure 68. Transmittance Component Caused by Carbon Dioxide for Sky Segment 4, Zenith Angle of 49.5°

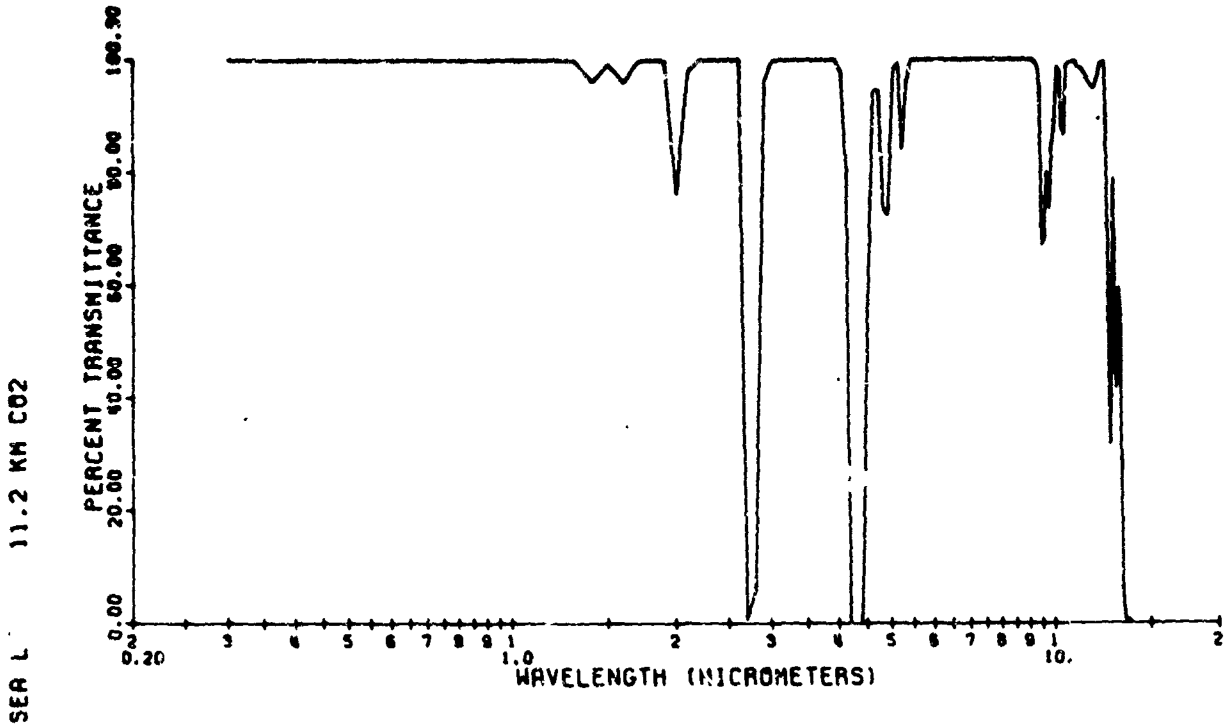


Figure 69. Transmittance Component Caused by Carbon Dioxide for Sky Segment 5, Zenith Angle of 56.6°

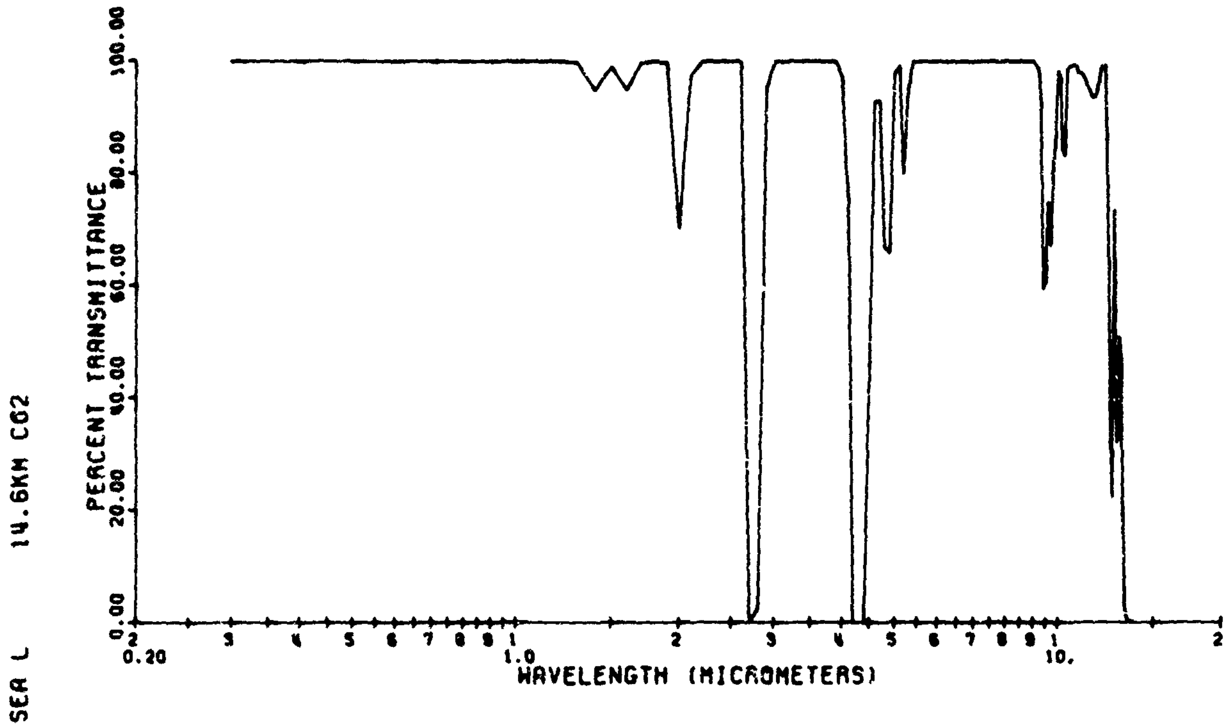


Figure 70. Transmittance Component Caused by Carbon Dioxide for Sky Segment 6, Zenith Angle of 63.2°

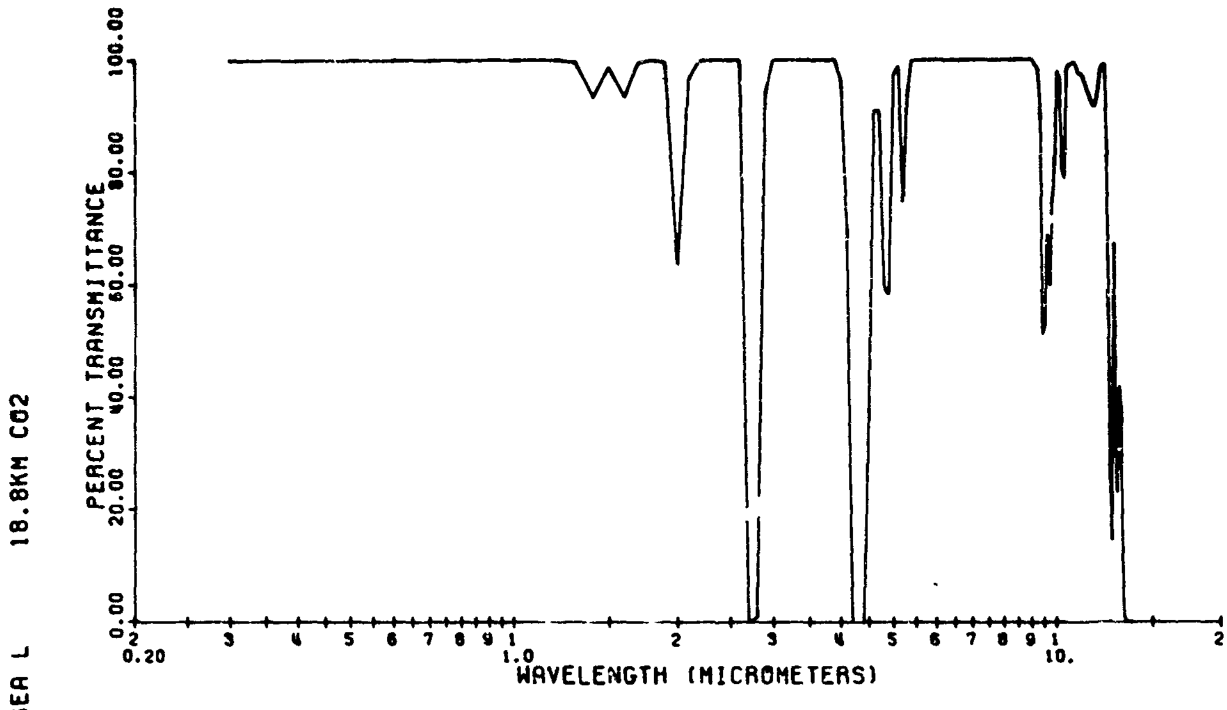


Figure 71. Transmittance Component Caused by Carbon Dioxide for Sky Segment 7, Zenith Angle of 69.5°

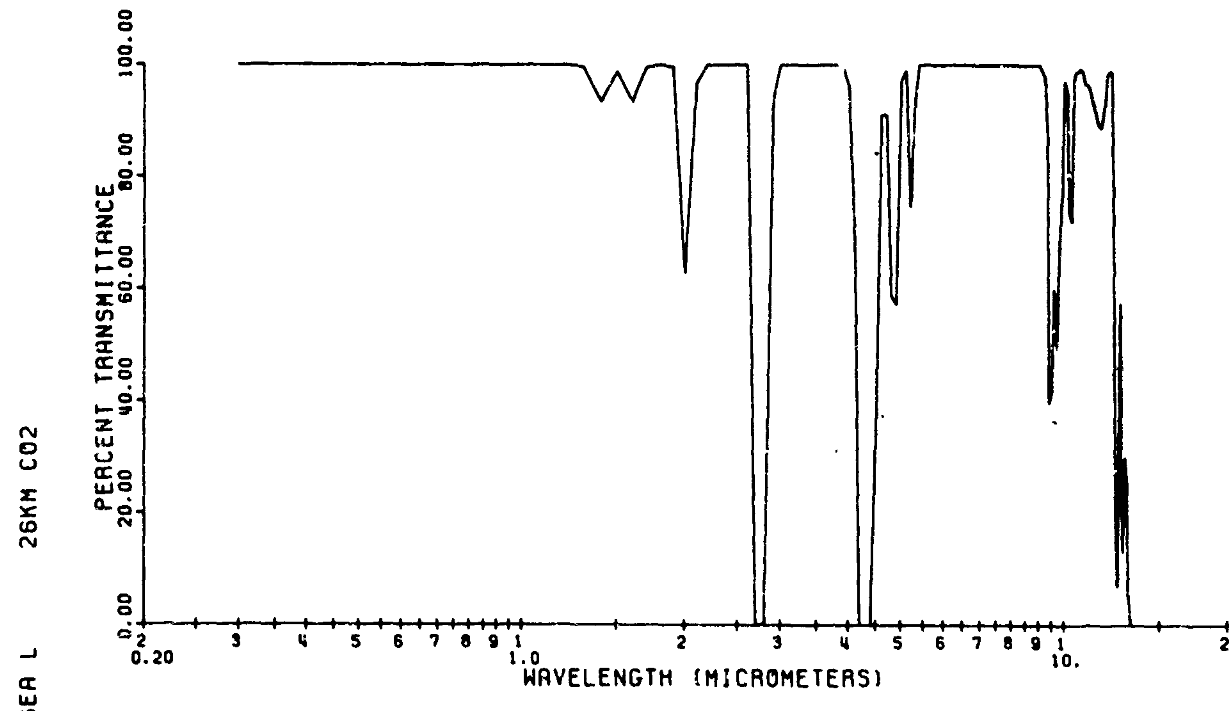


Figure 72. Transmittance Component Caused by Carbon Dioxide for Sky Segment 8, Zenith Angle of 75.5°

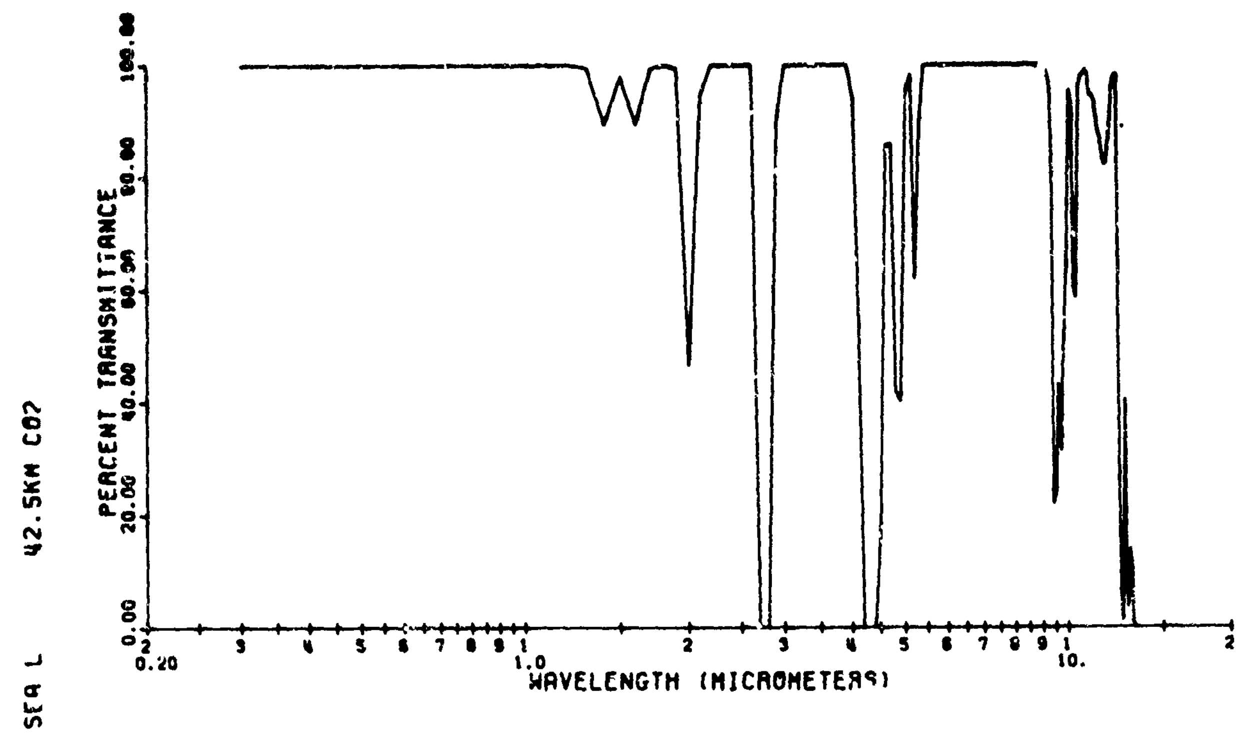


Figure 73. Transmittance Component Caused by Carbon Dioxide for Sky Segment 9, Zenith Angle of 81.4°

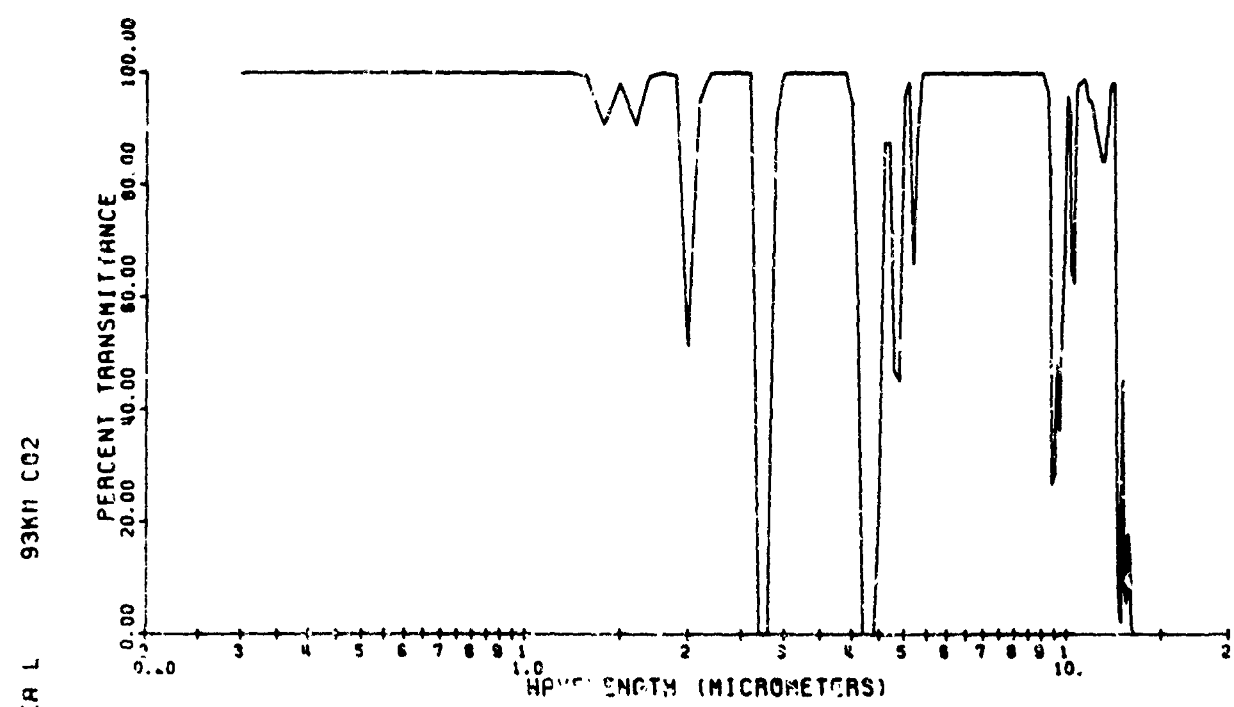


Figure 74. Transmittance Component Caused by Carbon Dioxide for Sky Segment 10, Zenith Angle of 87.2°

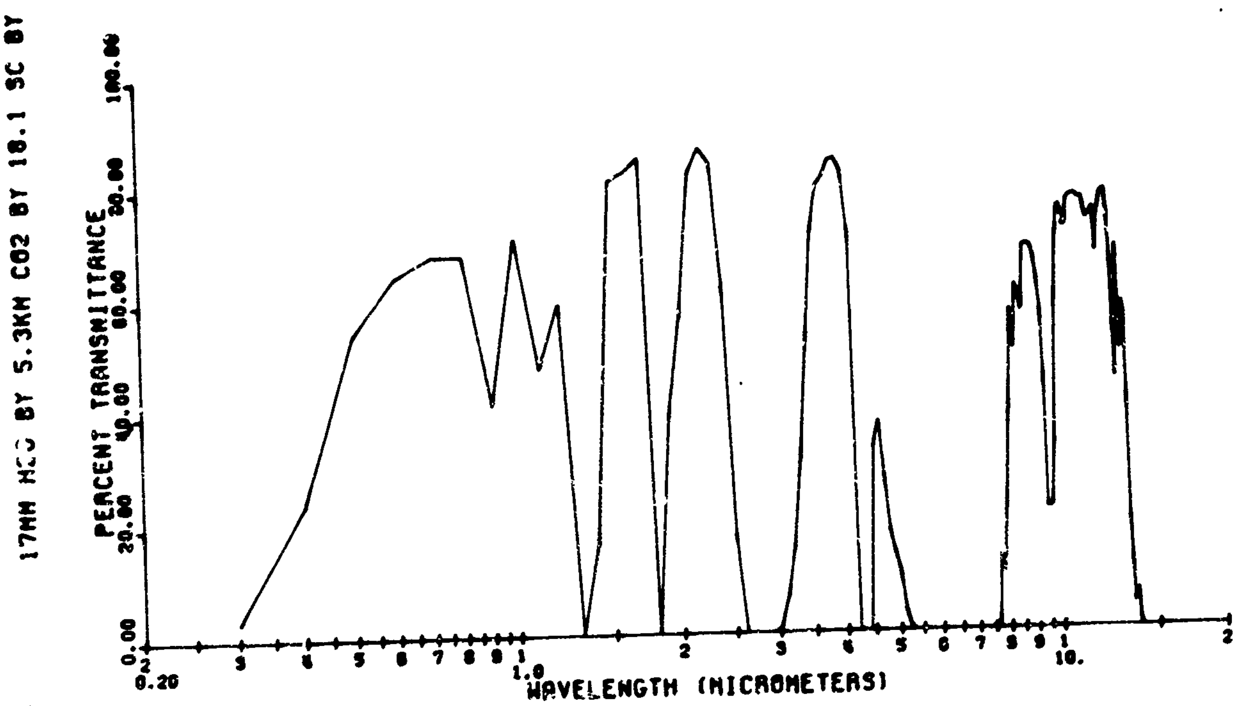


Figure 75. Atmospheric Transmittance for Sky Segment 1, Zenith Angle of 18.1°

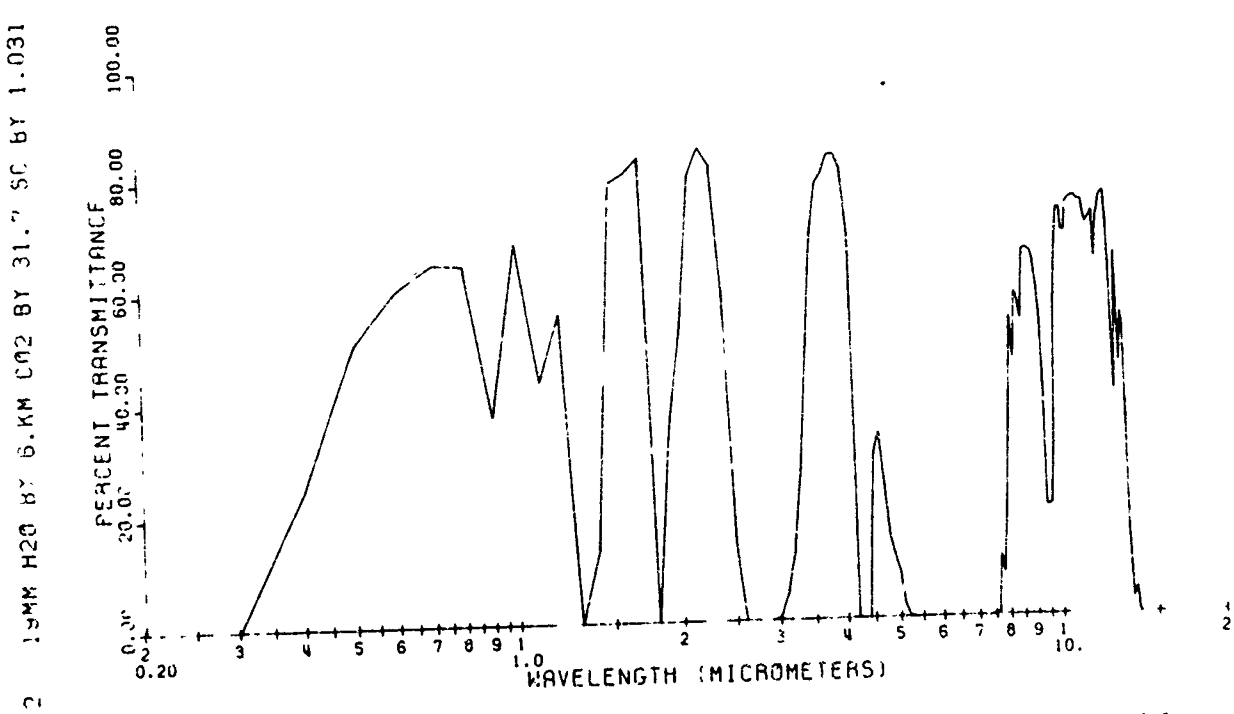


Figure 76. Atmospheric Transmittance for Sky Segment 2, Zenith Angle of 31.7°

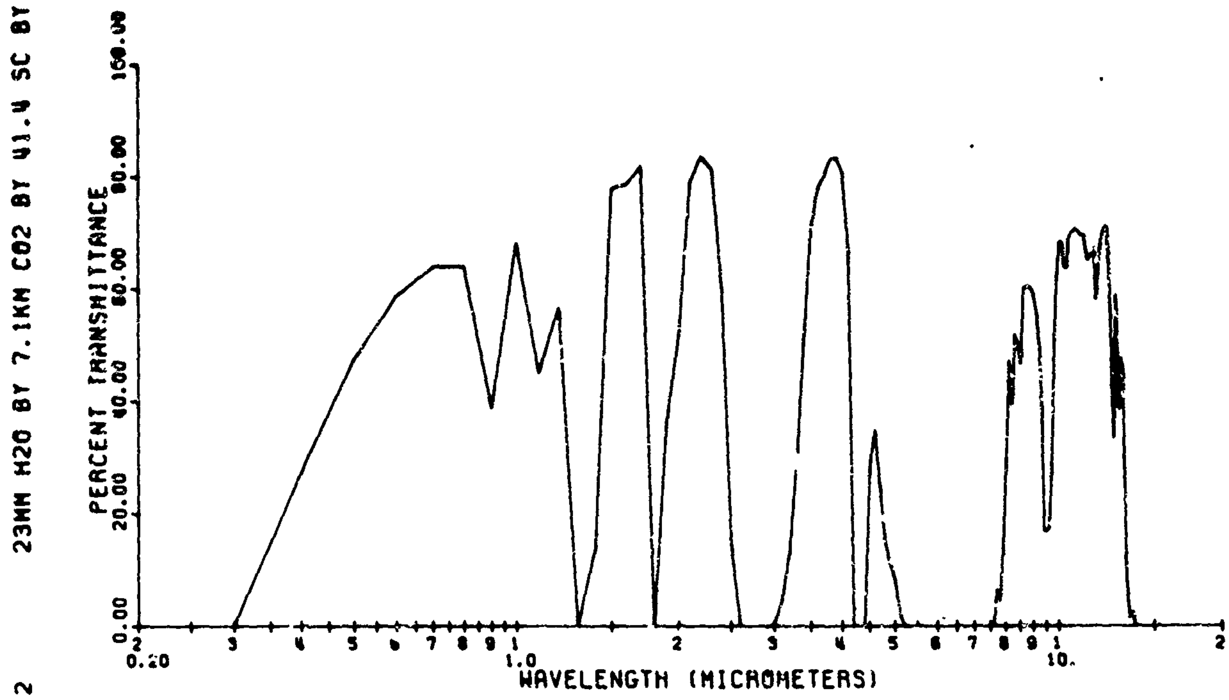


Figure 77. Atmospheric Transmittance for Sky Segment 3, Zenith Angle of 41.4°

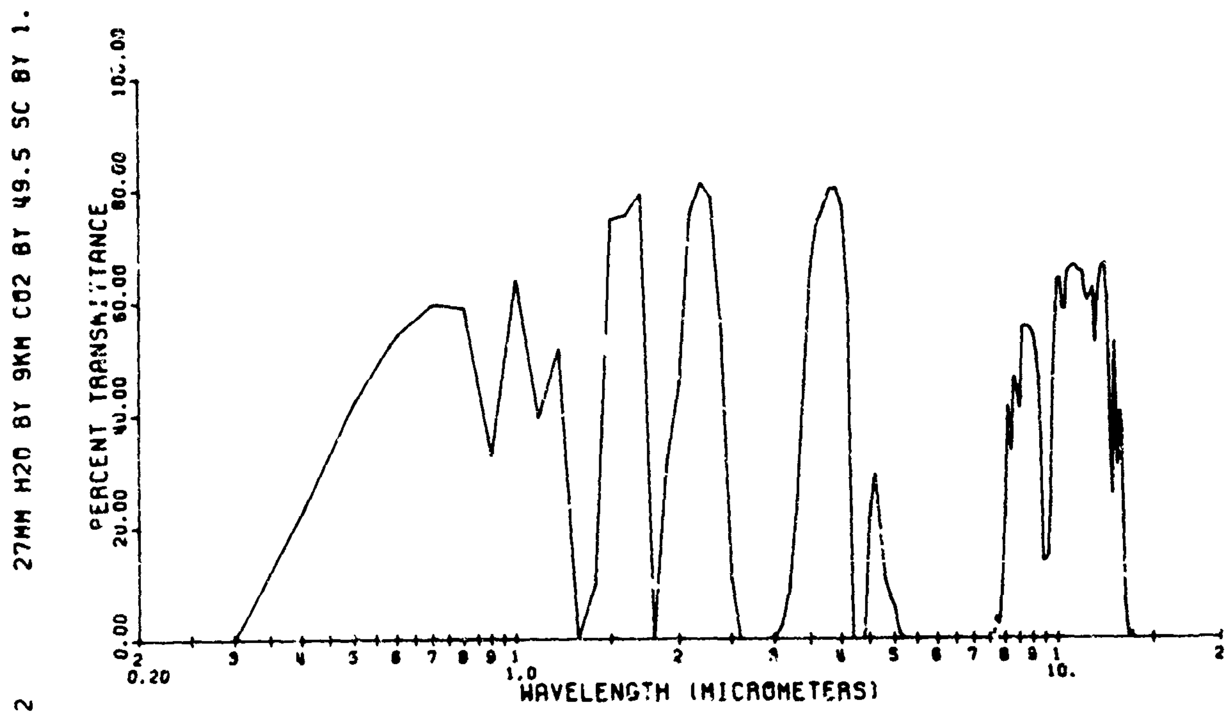


Figure 78. Atmospheric Transmittance for Sky Segment 4, Zenith Angle of 49.5°

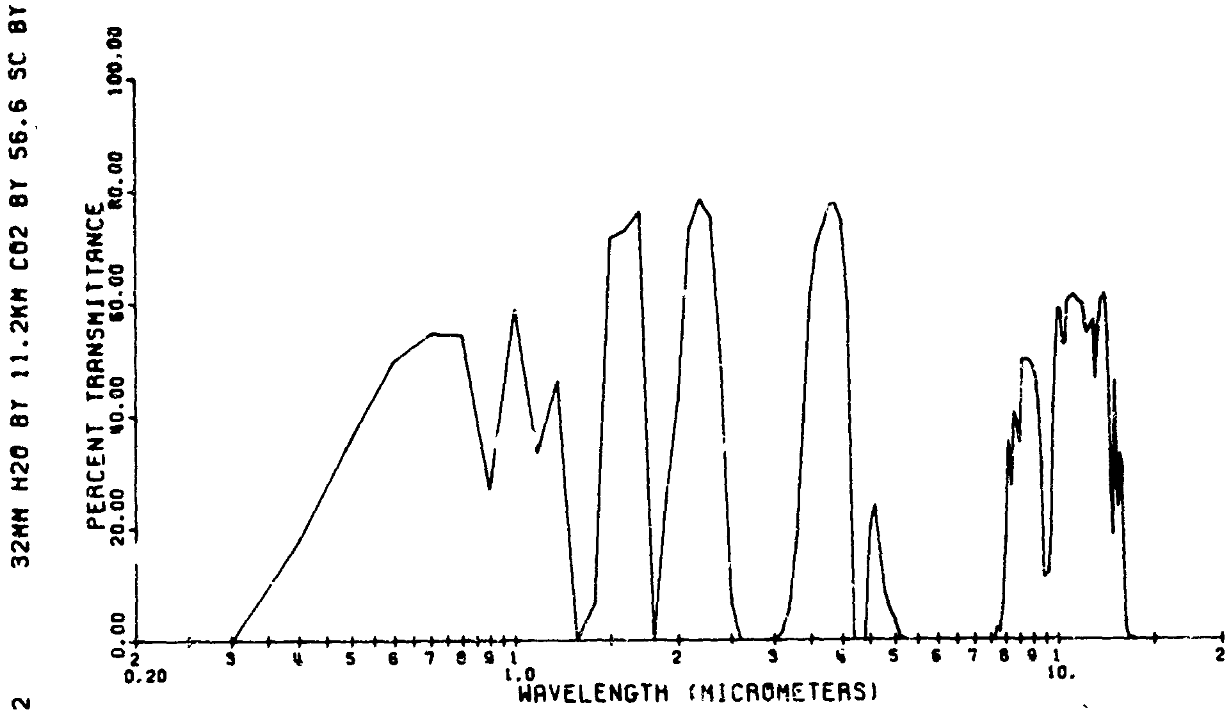


Figure 79. Atmospheric Transmittance for Sky Segment 5, Zenith Angle of 56.6°

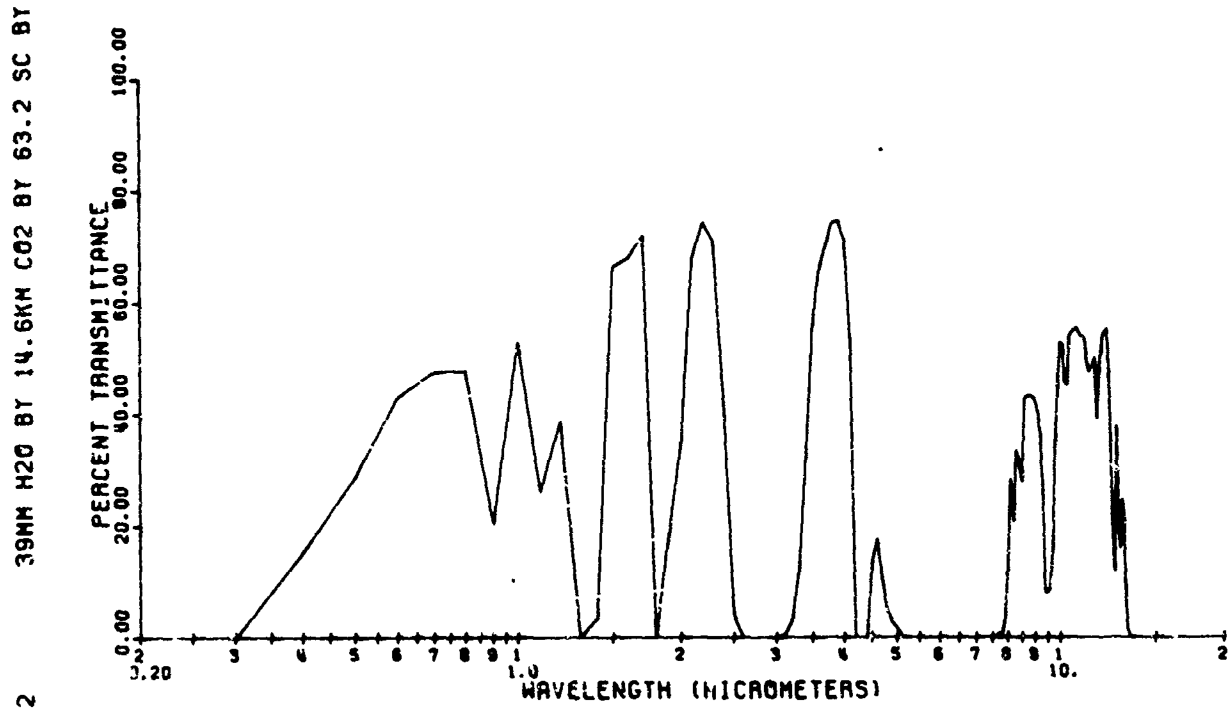


Figure 80. Atmospheric Transmittance for Sky Segment 6, Zenith Angle of 63.2°

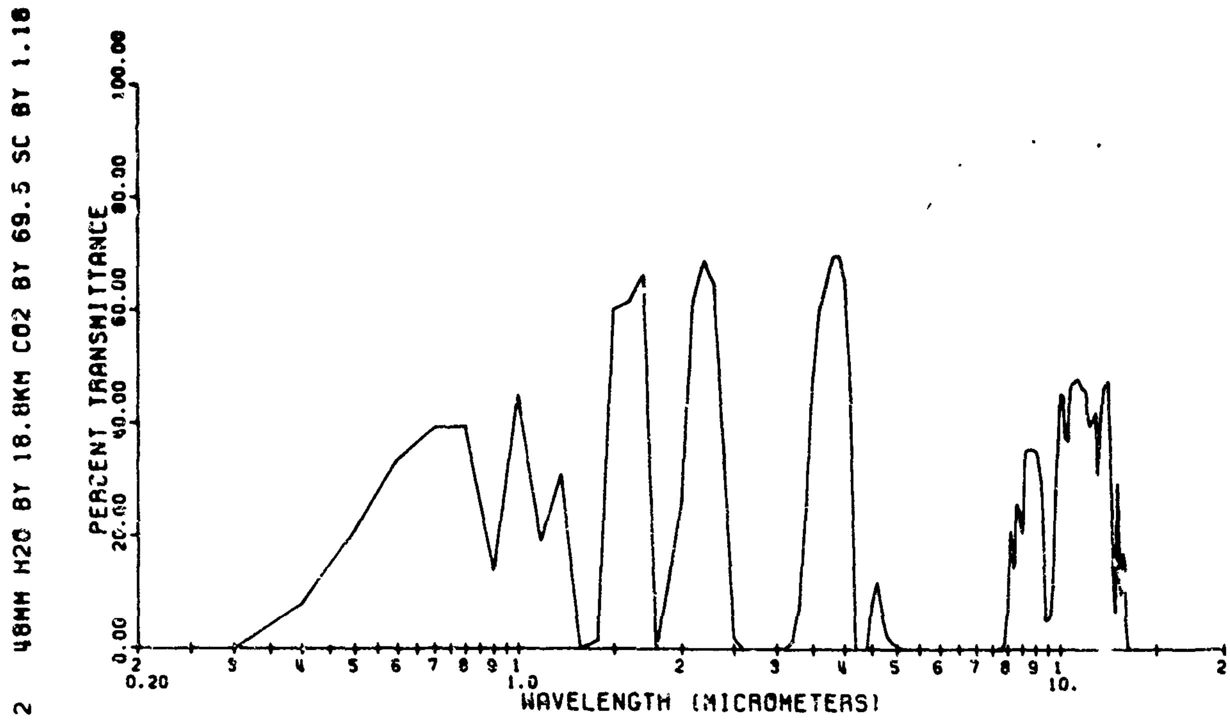


Figure 81. Atmospheric Transmittance for Sky Segment 7, Zenith Angle of 69.5°

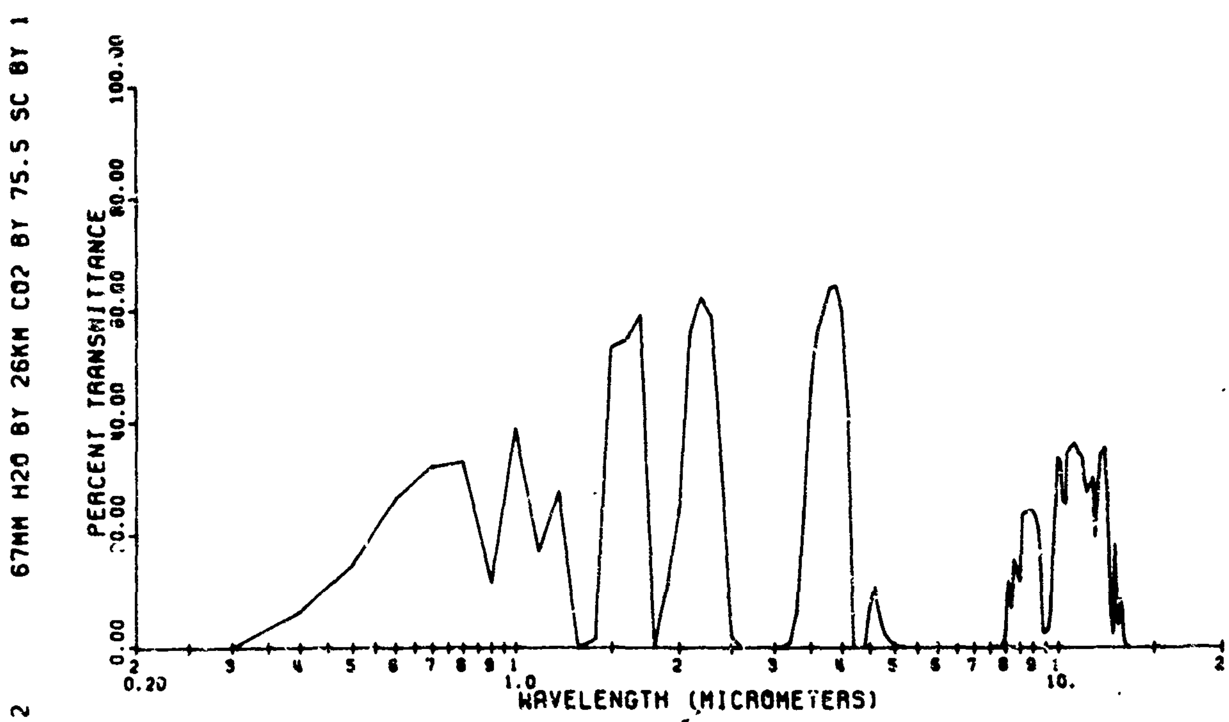


Figure 82. Atmospheric Transmittance for Sky Segment 8, Zenith Angle of 75.5°

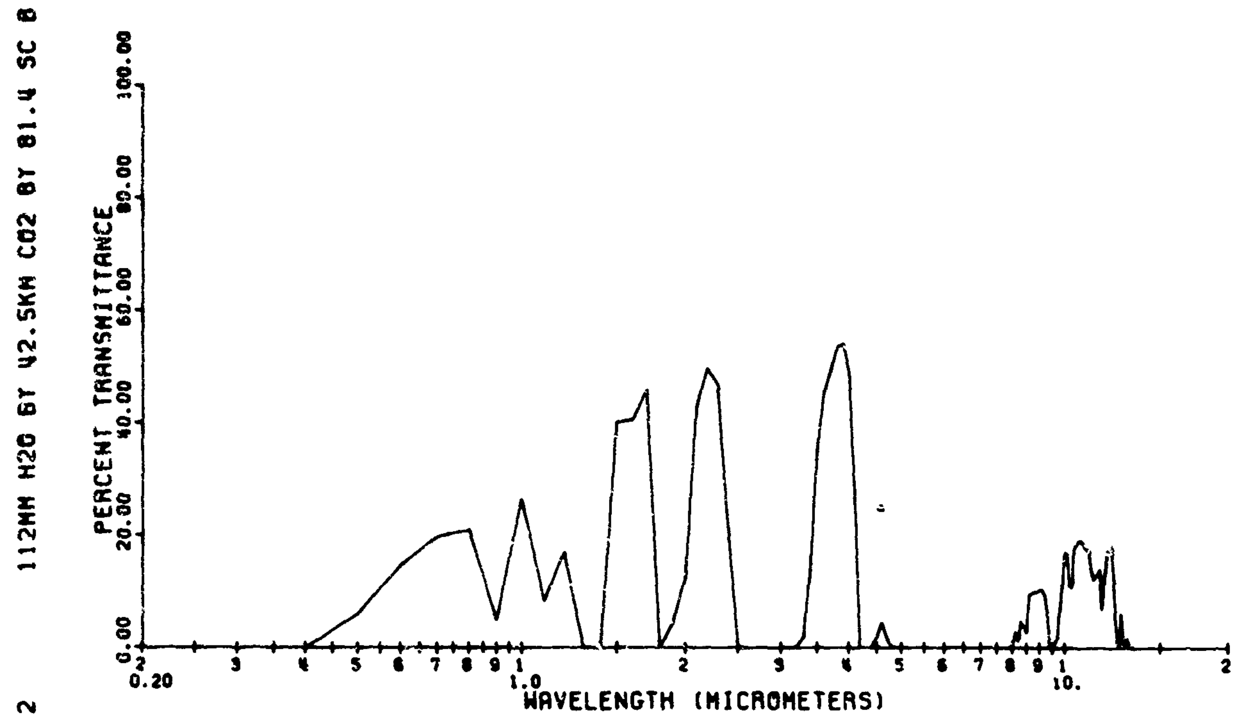


Figure 83. Atmospheric Transmittance for Sky Segment 9, Zenith Angle of 81.4°

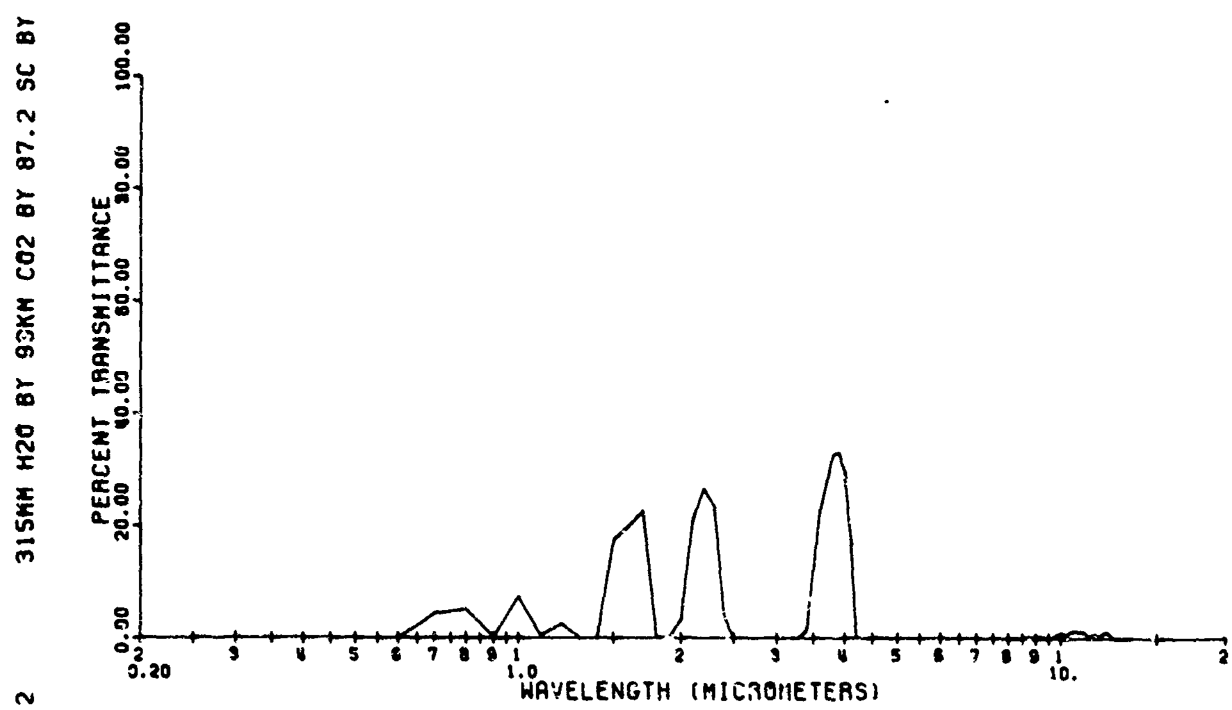


Figure 84. Atmospheric Transmittance for Sky Segment 10, Zenith Angle of 87.2°

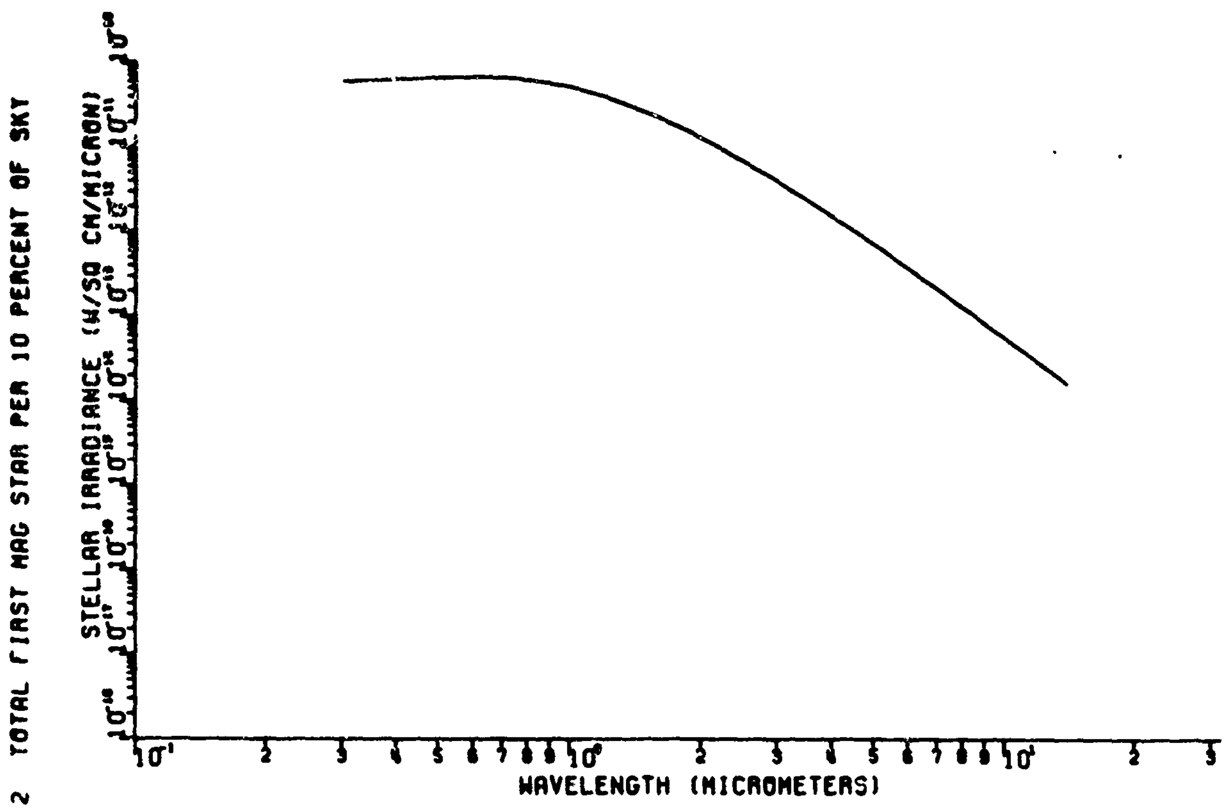


Figure 85. Spectral Stellar Irradiance for 0.1 of the Sky Above the Atmosphere

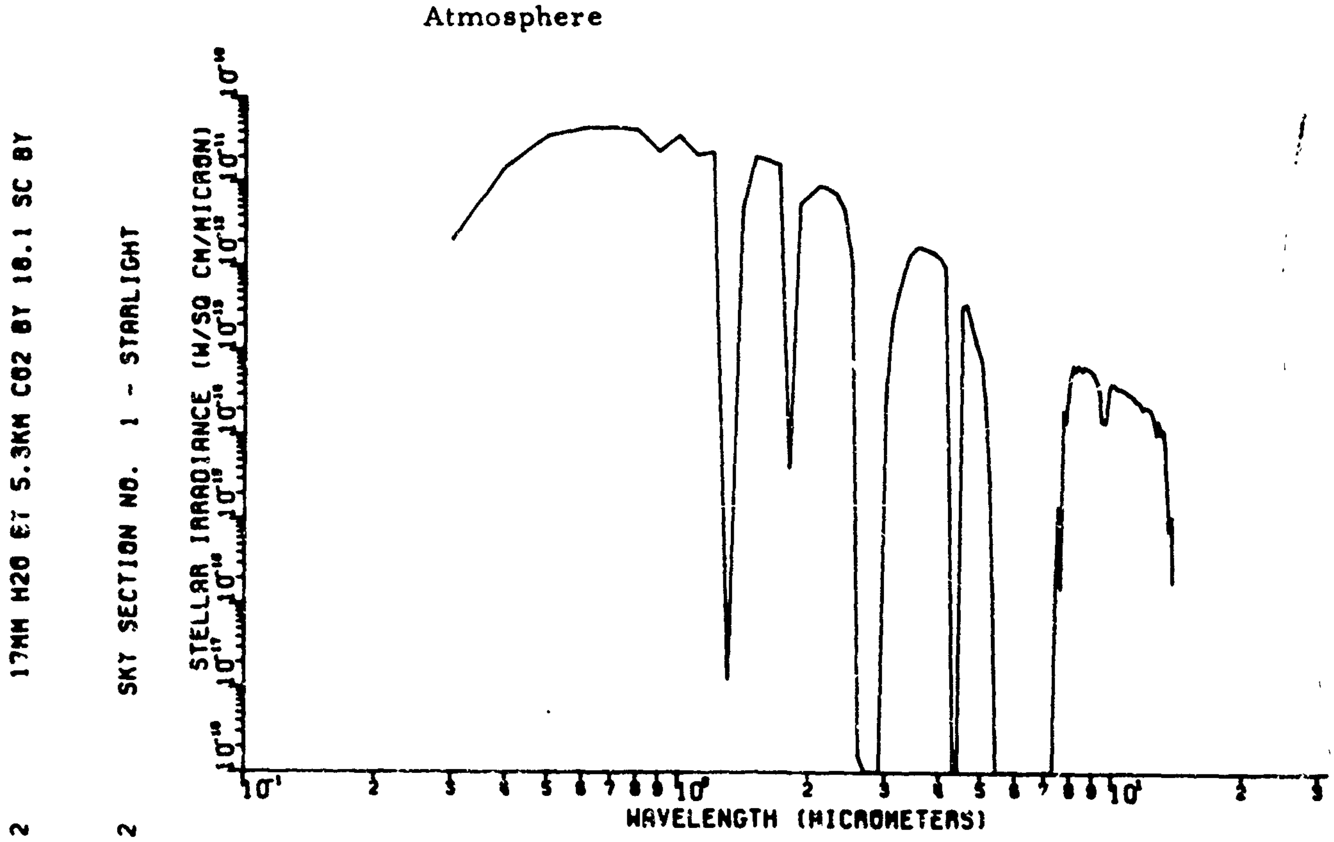


Figure 86. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 1, Zenith Angle of 18.1°

23MM H2O BY 7.1KM CO2 BY 41.4 SC BY

2

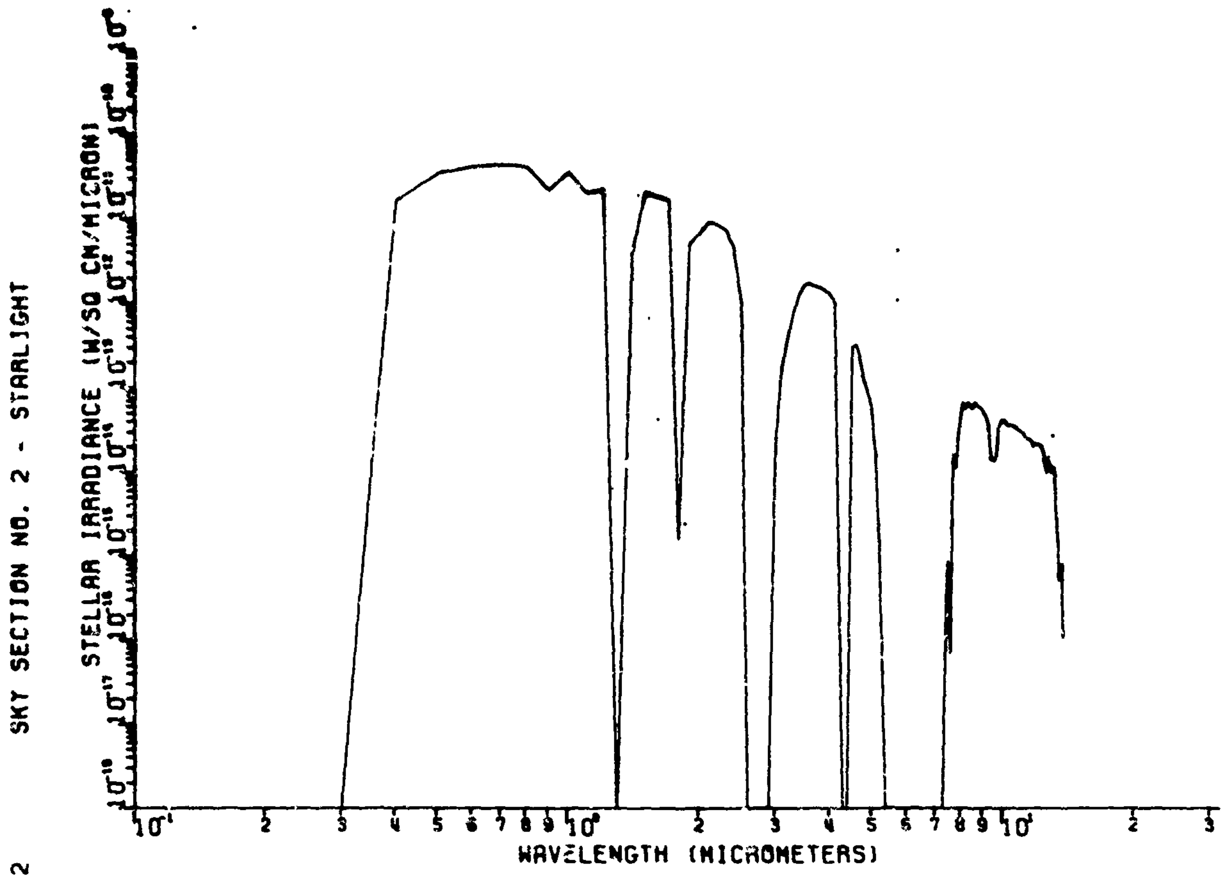


Figure 87. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 2, Zenith Angle of 31.7°

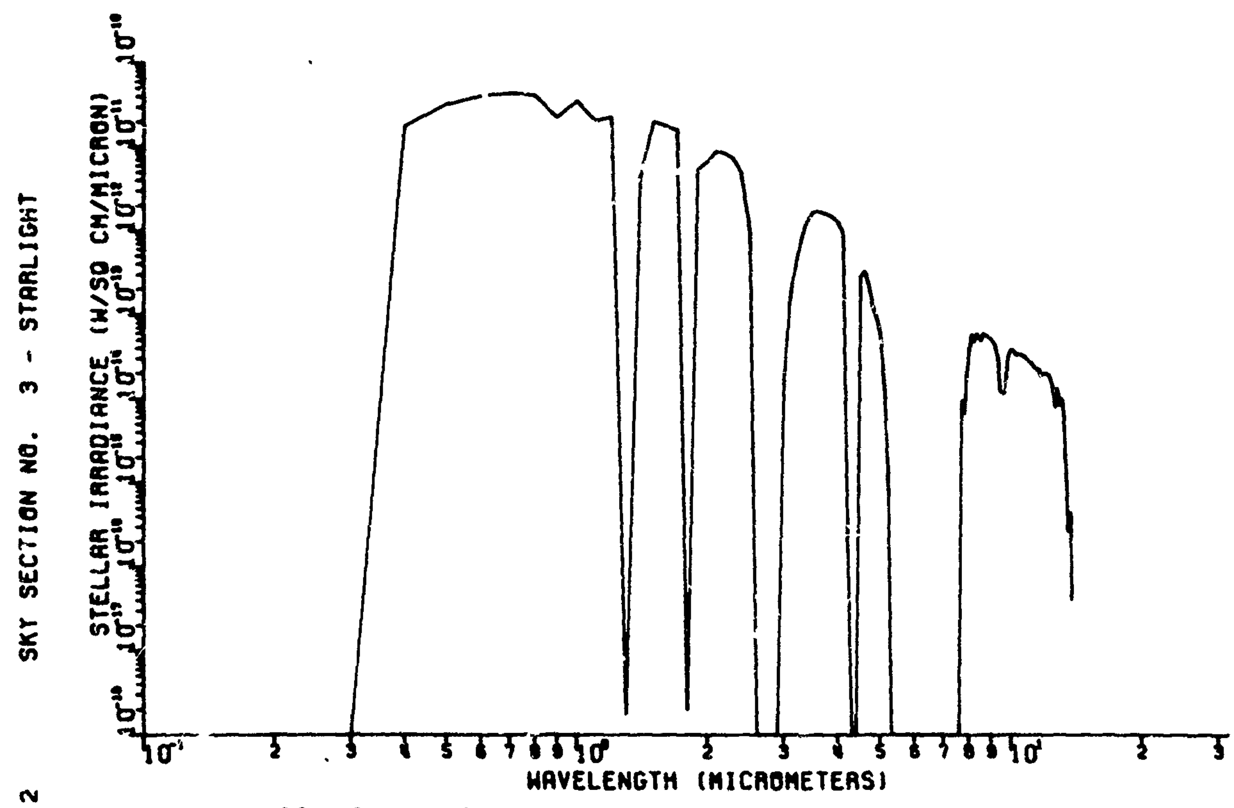


Figure 88. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 3, Zenith Angle of 41.4°

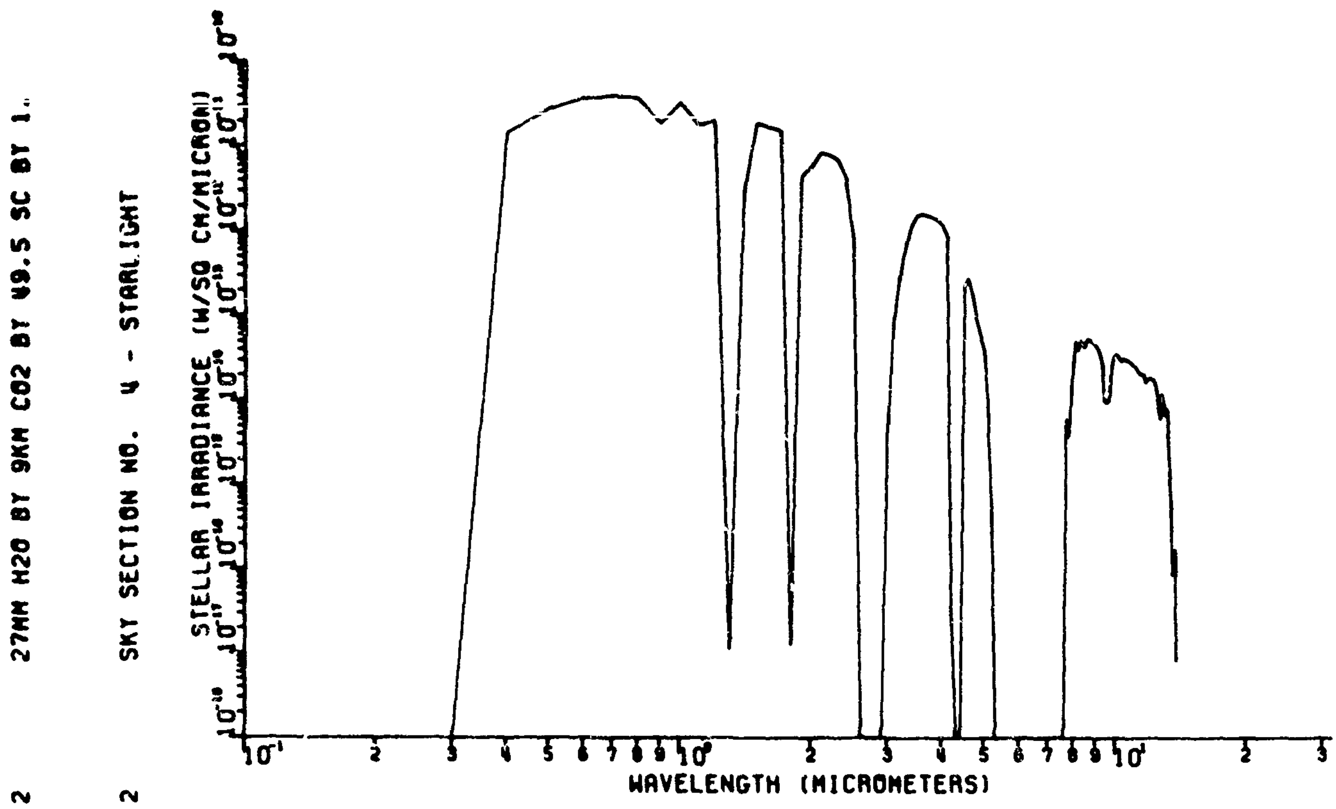


Figure 89. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 4, Zenith Angle of 49.5°

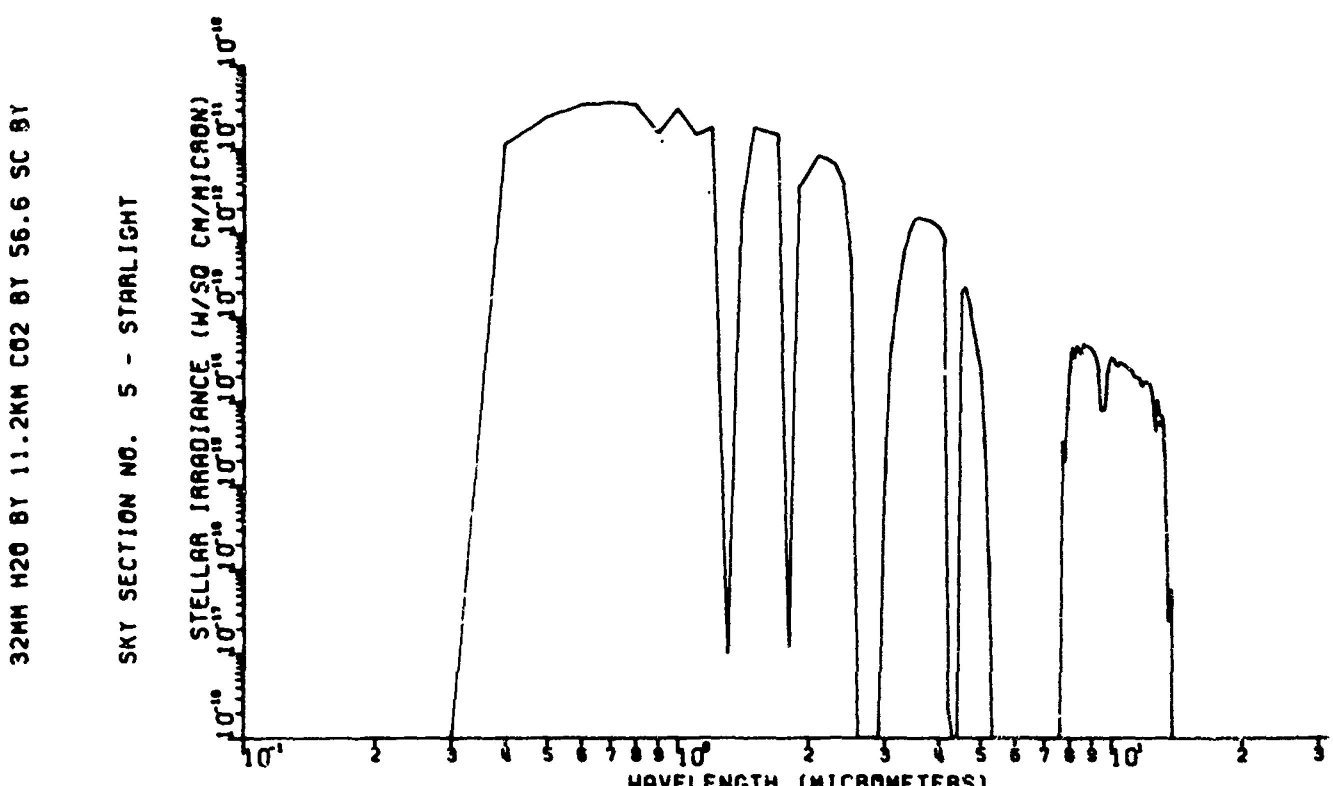


Figure 90. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 5, Zenith Angle of 56.6°

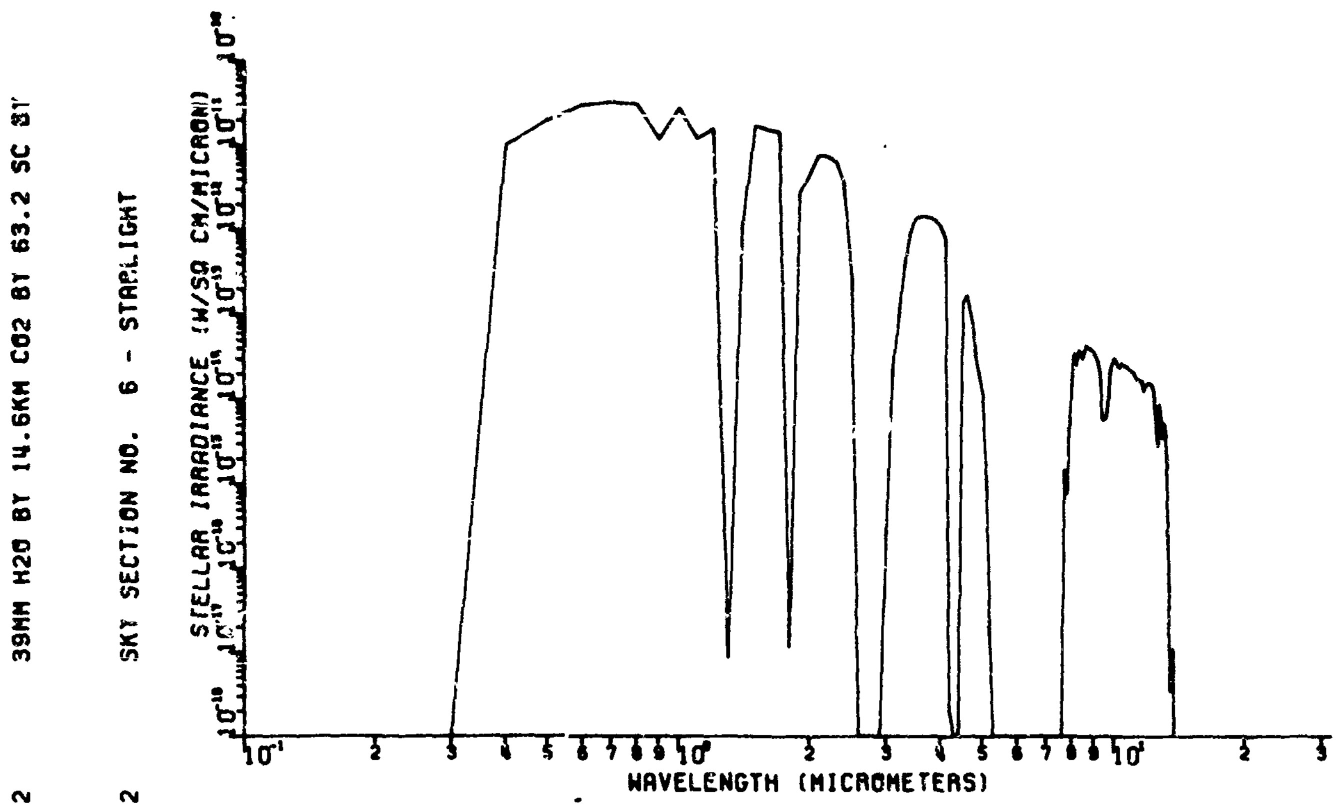


Figure 91. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 6, Zenith Angle of 63.2°

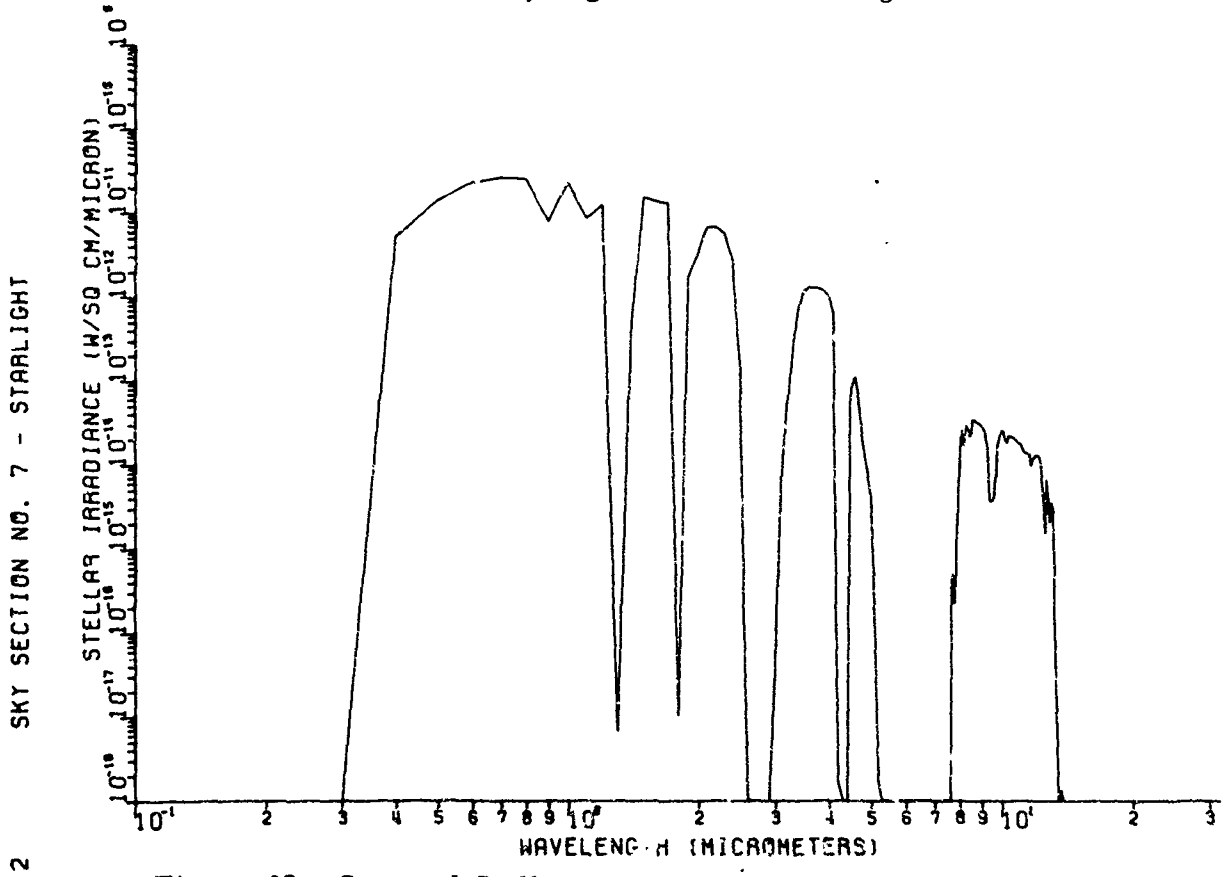


Figure 92. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 7, Zenith Angle of 69.5°

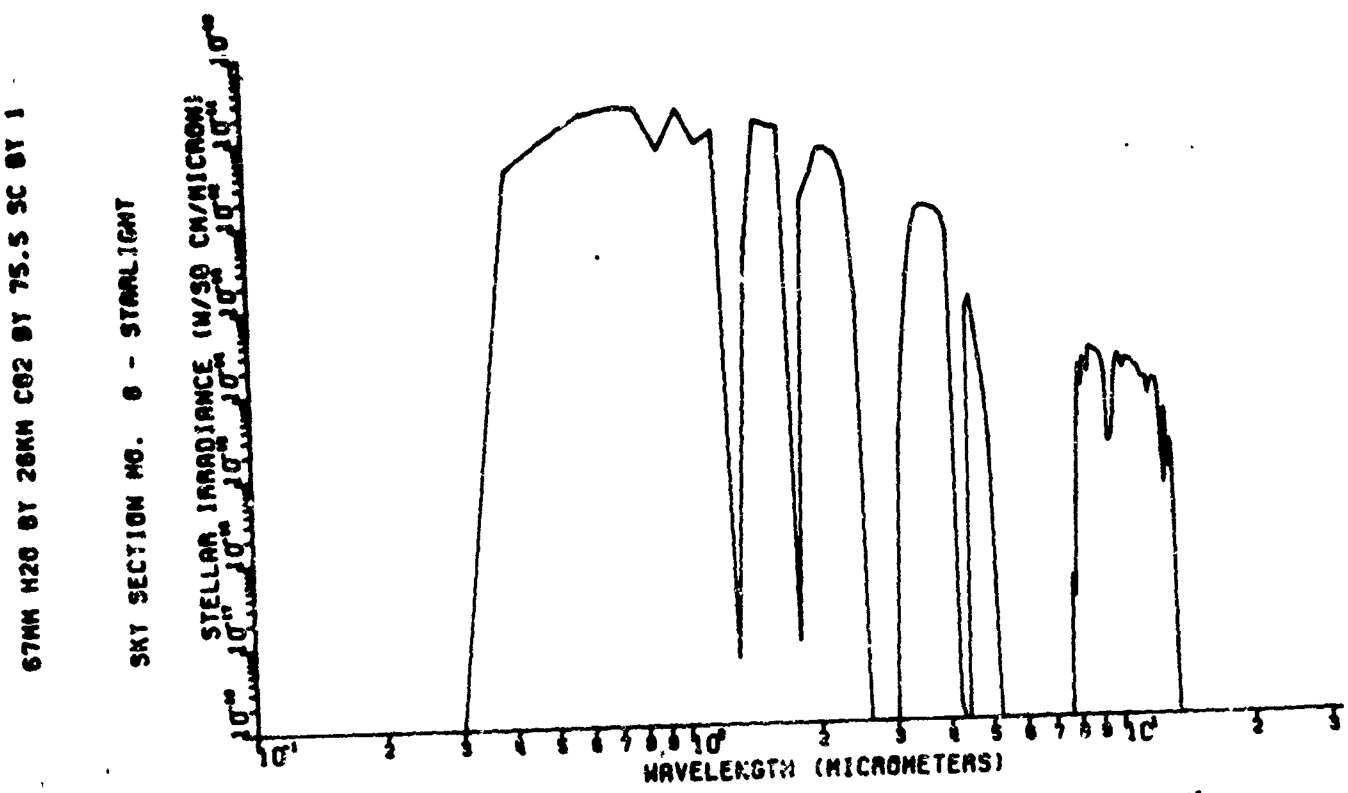


Figure 93. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 8, Zenith Angle of 75.5°

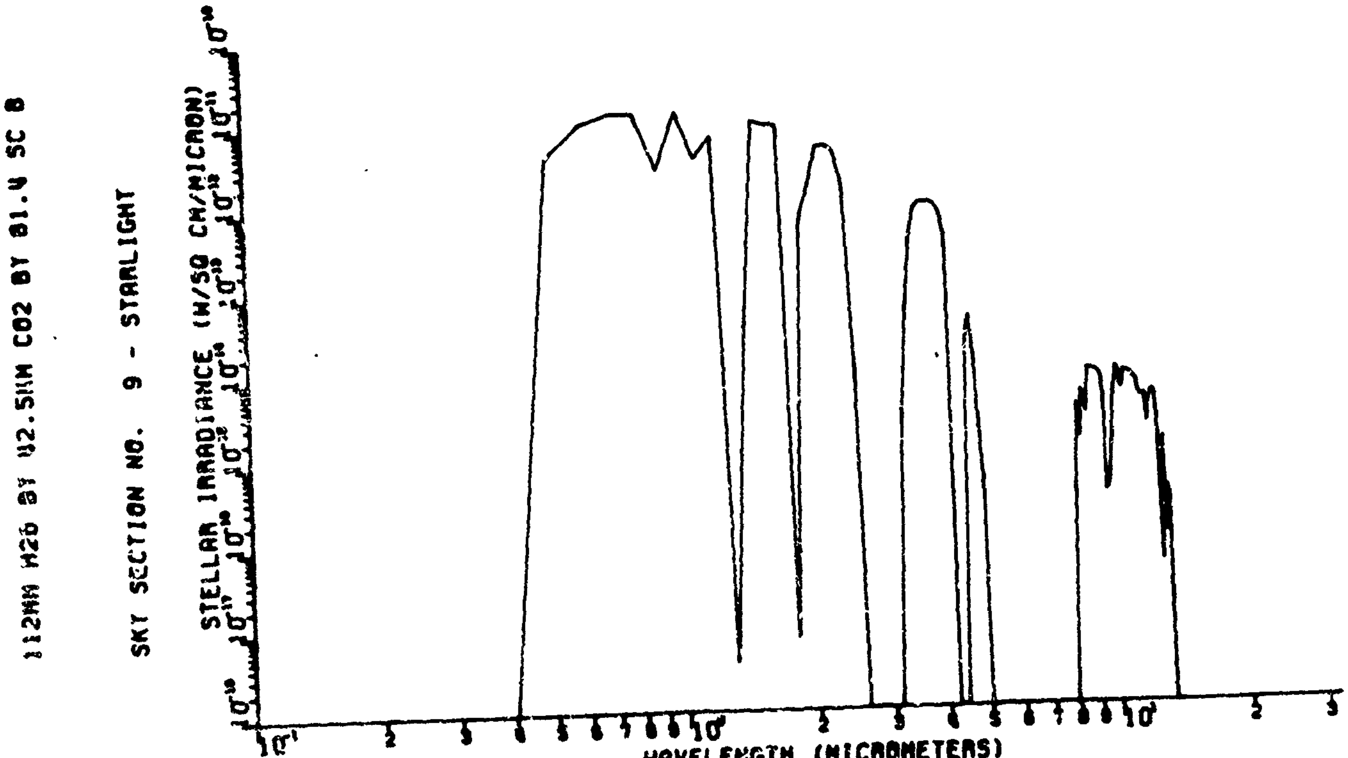


Figure 94. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Seg ent 9, Zenith Angle of 81.4°

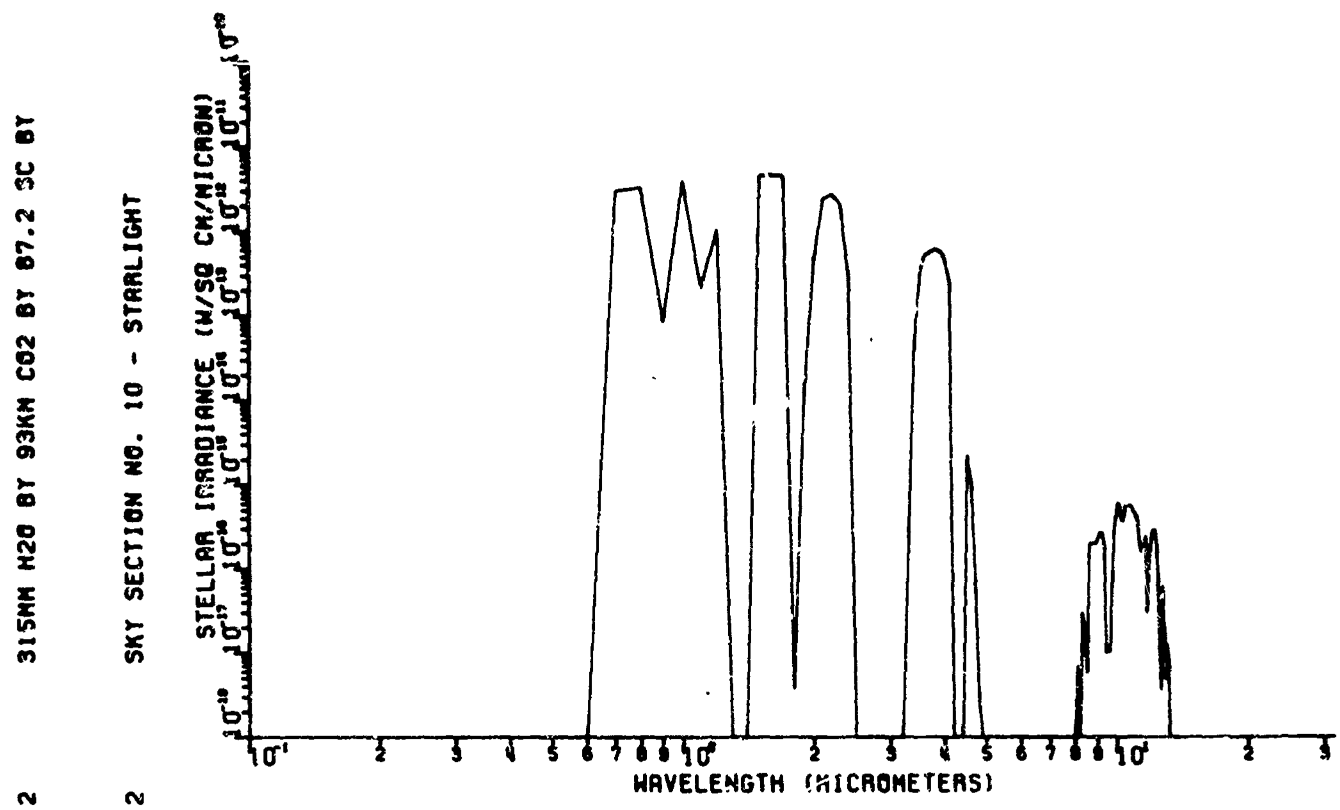


Figure 95. Spectral Stellar Irradiance for 0.1 of the Sky at the Surface, Sky Segment 10, Zenith Angle of 87.2°

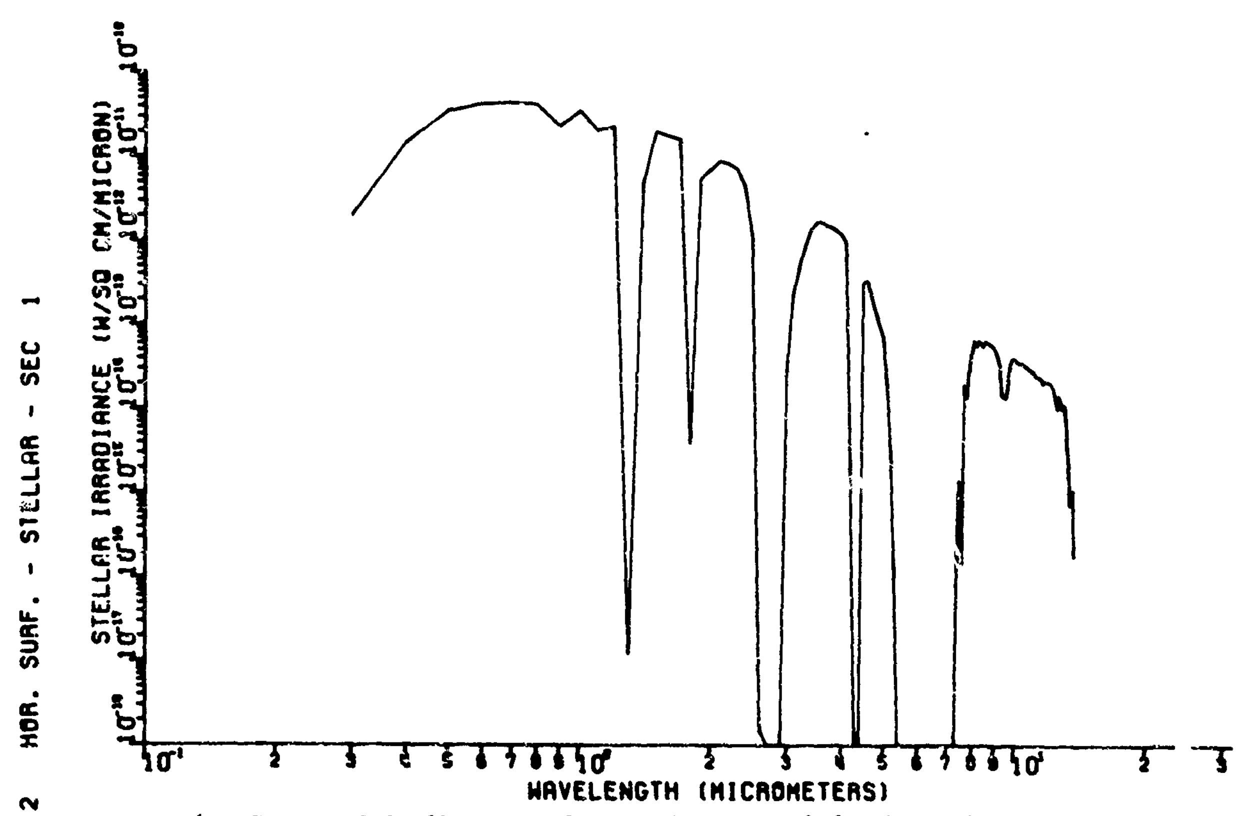


Figure 96. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 1, Zenith Angle of 18.1°

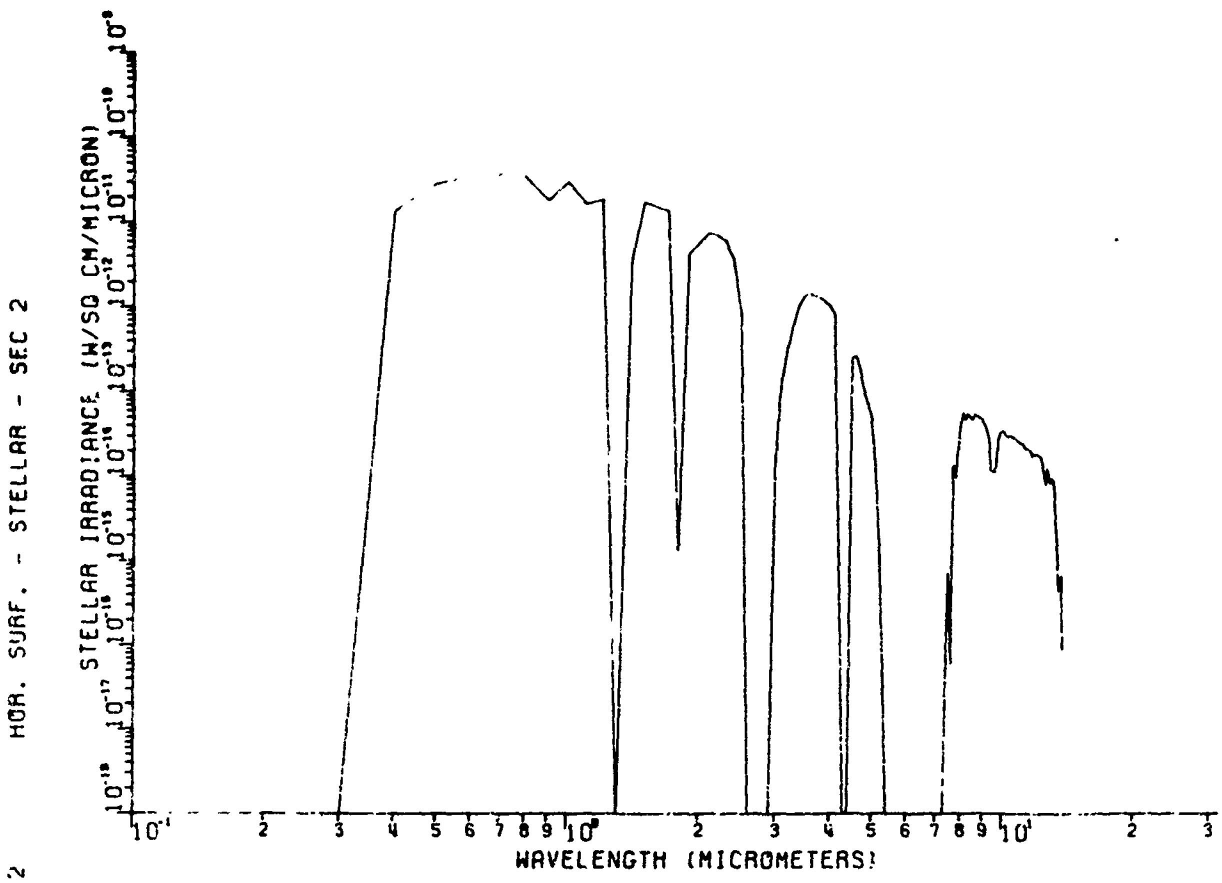


Figure 97. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 2, Zenith Angle of 31.7°

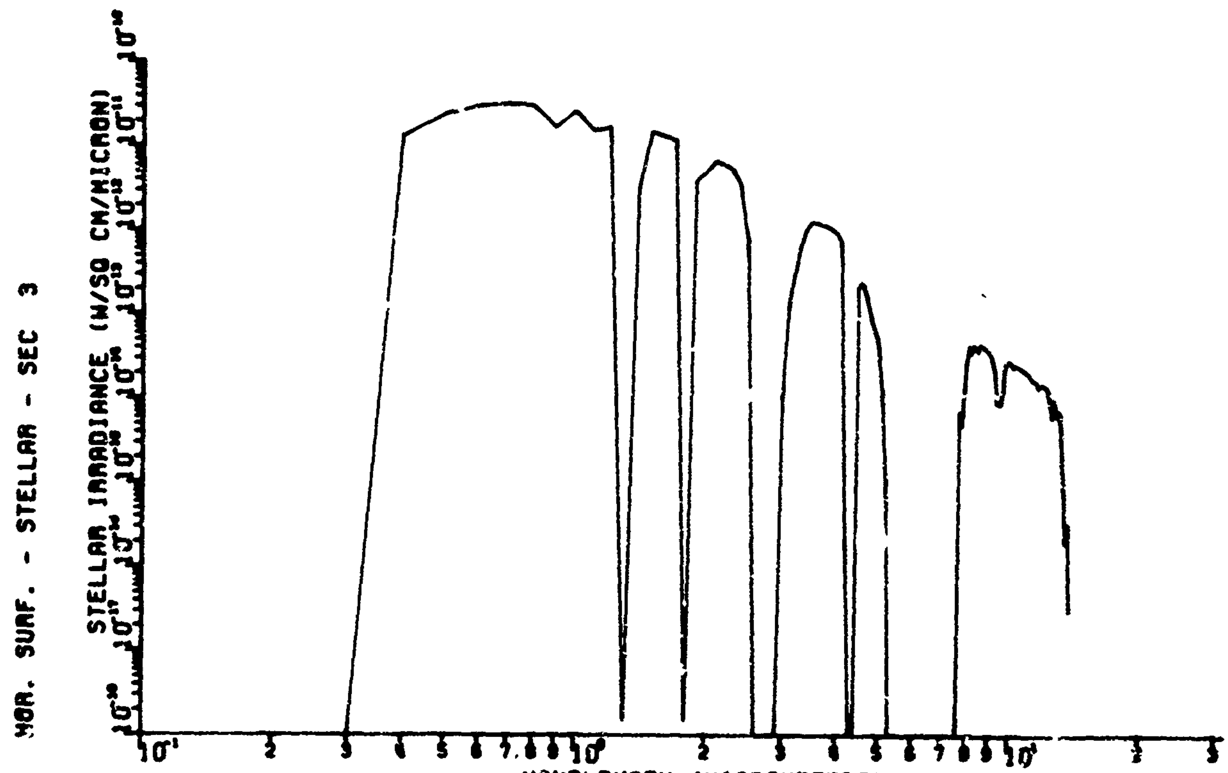


Figure 98. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 3, Zenith Angle of 41.4°

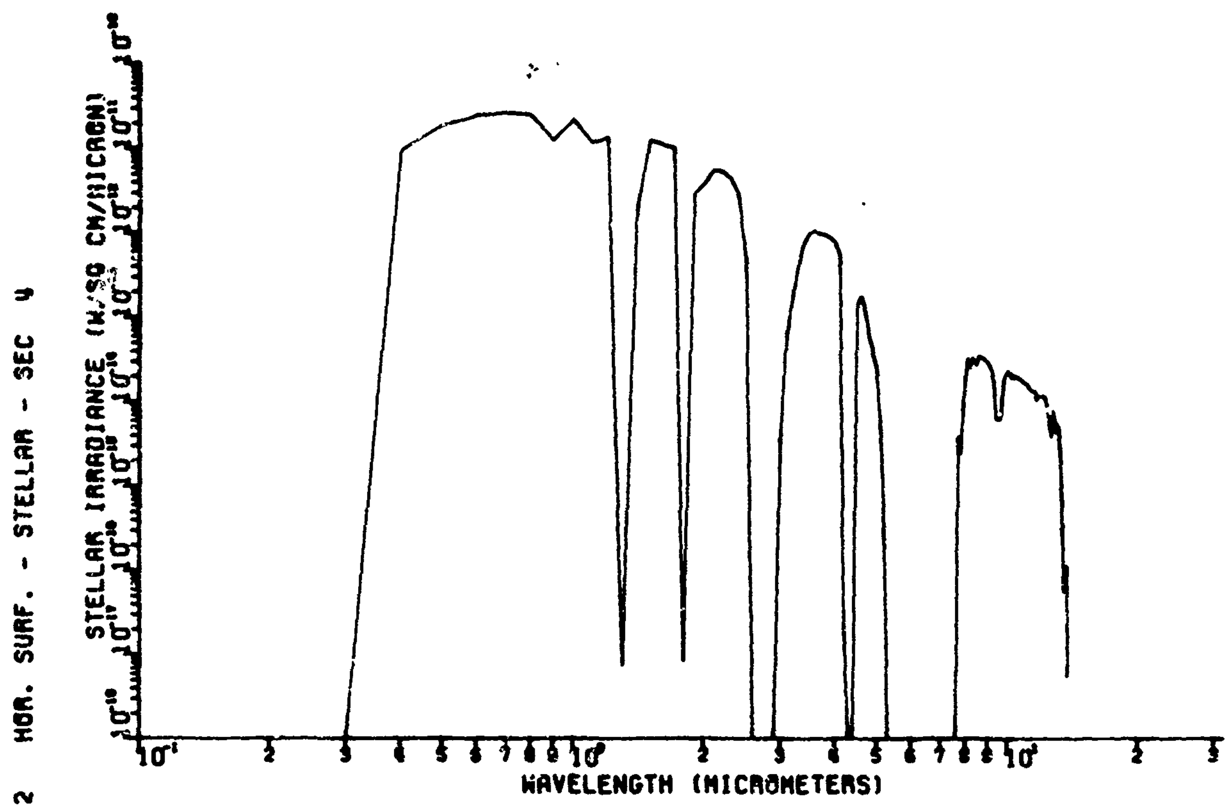


Figure 99. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 4, Zenith Angle of 49.5°

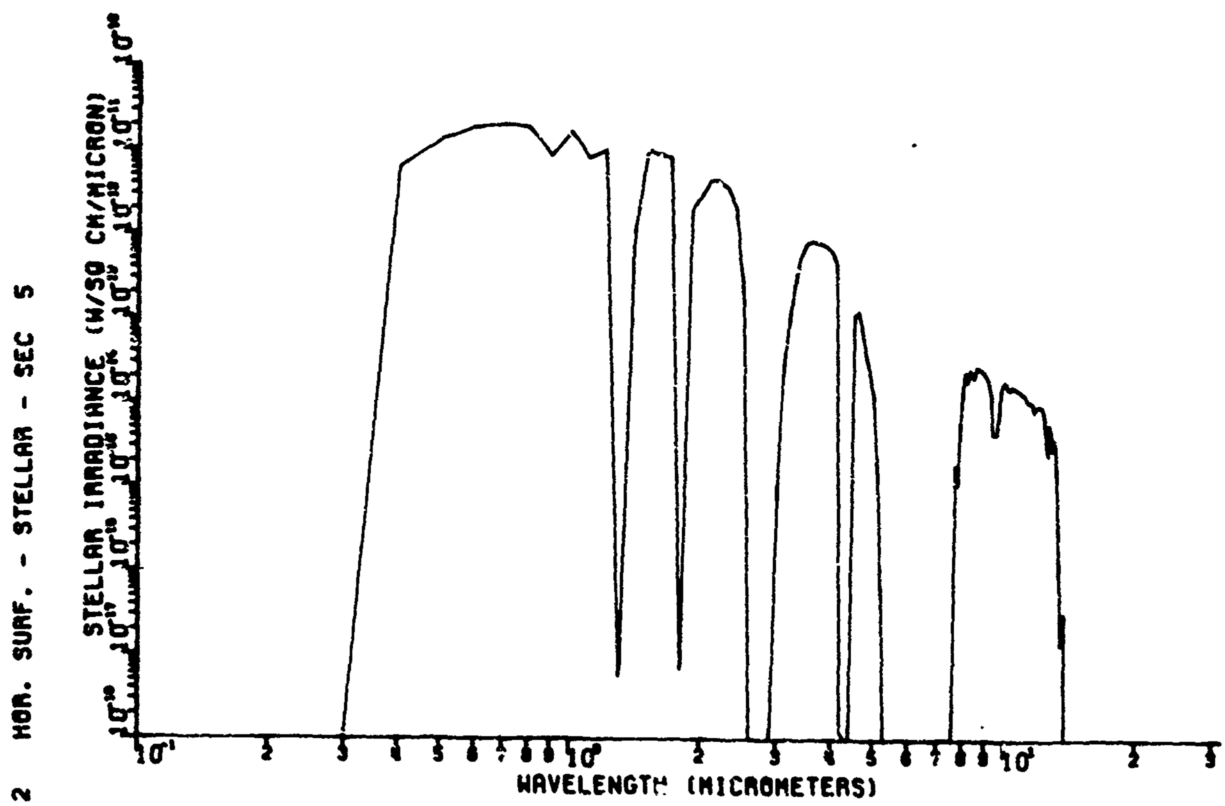


Figure 100. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 5, Zenith Angle of 56.6°

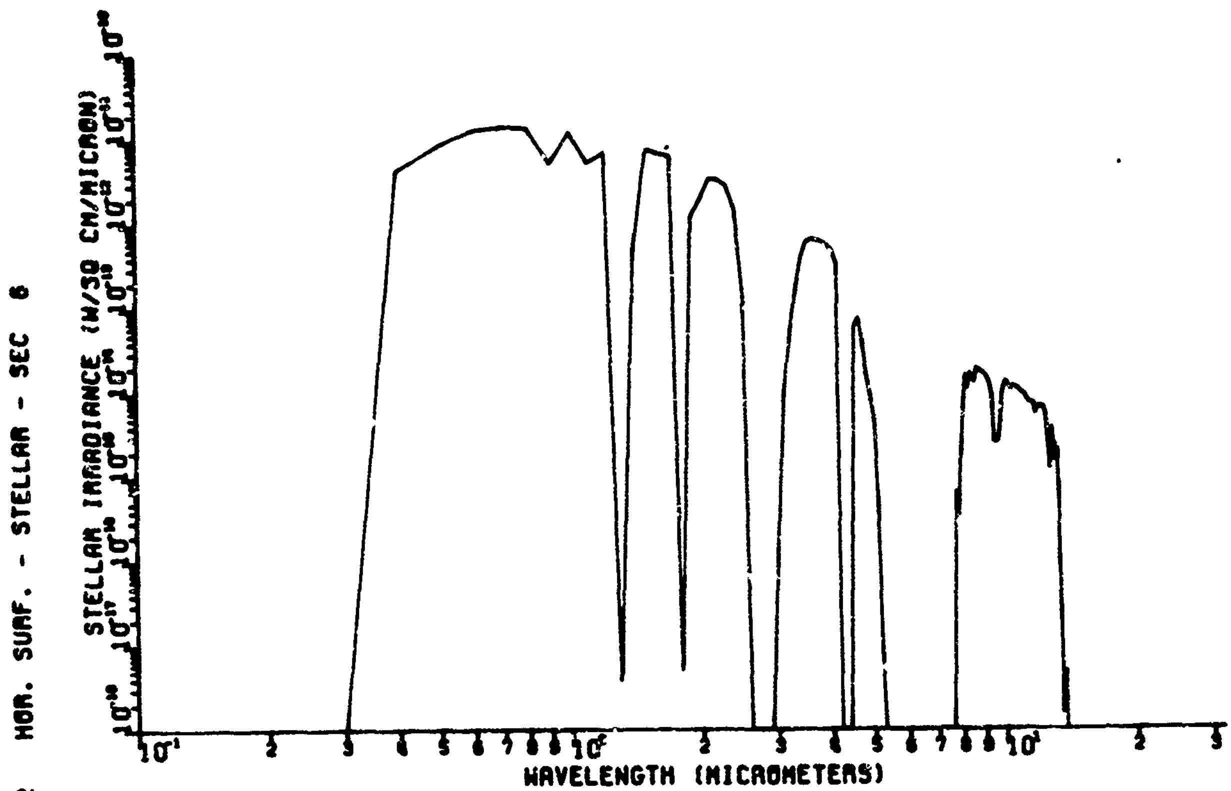


Figure 101. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 6, Zenith Angle of 63.2°

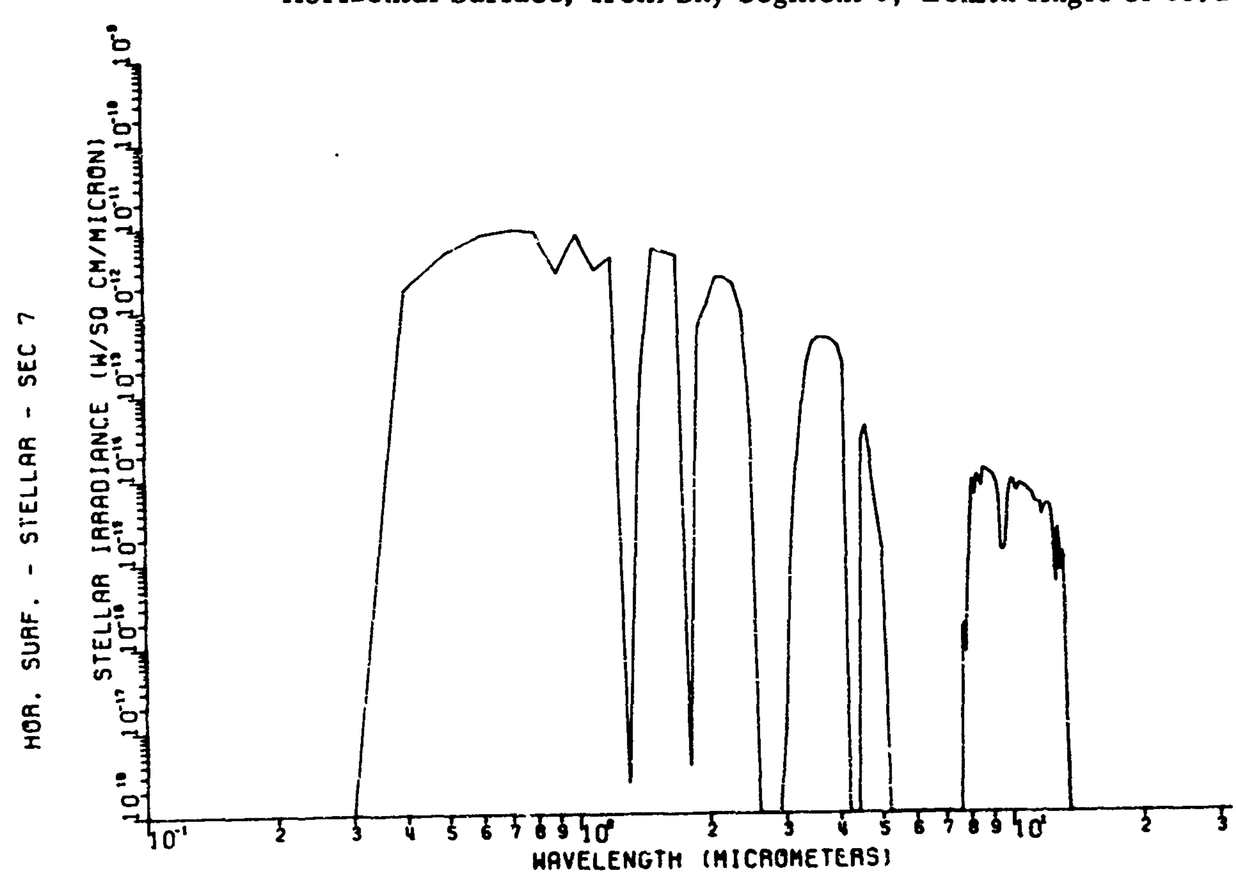


Figure 102. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 7, Zenith Angle of 69.5°

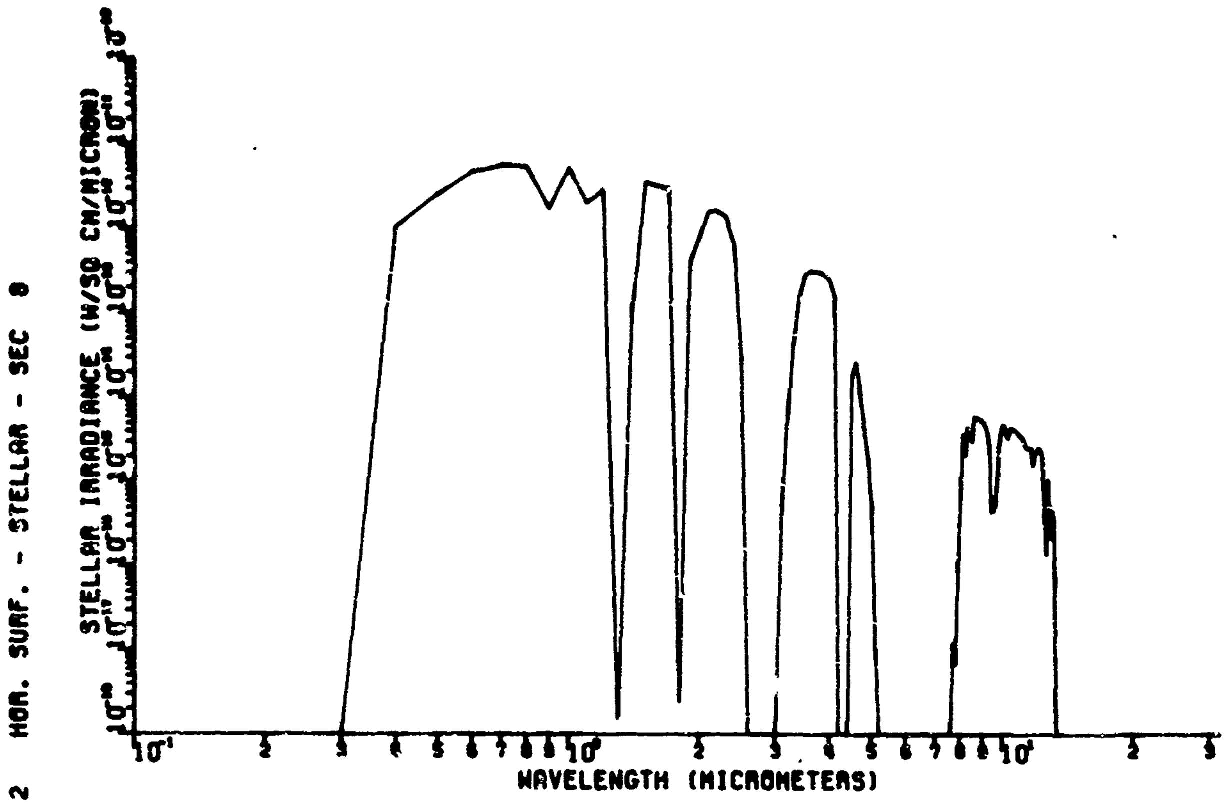


Figure 103. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 8, Zenith Angle of 75.5°

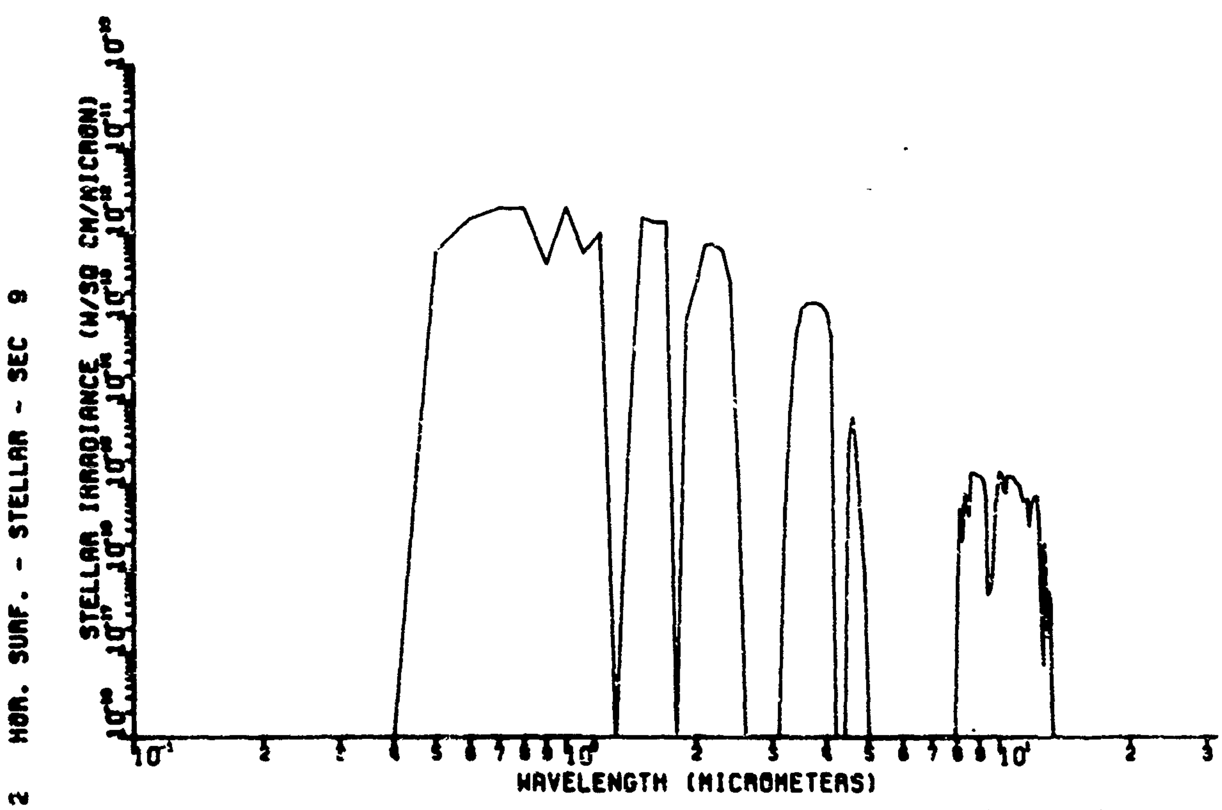


Figure 104. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 9, Zenith Angle of 81.4°

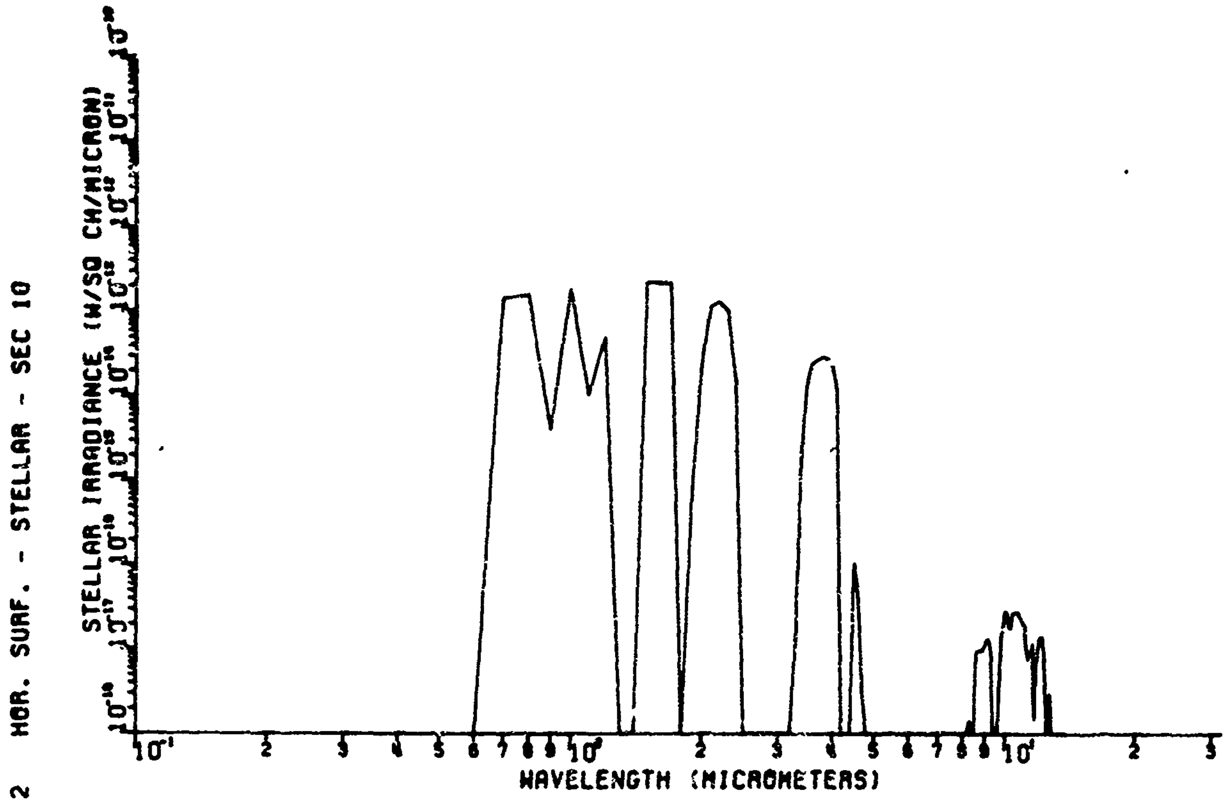


Figure 105. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 10, Zenith Angle of 87.2°

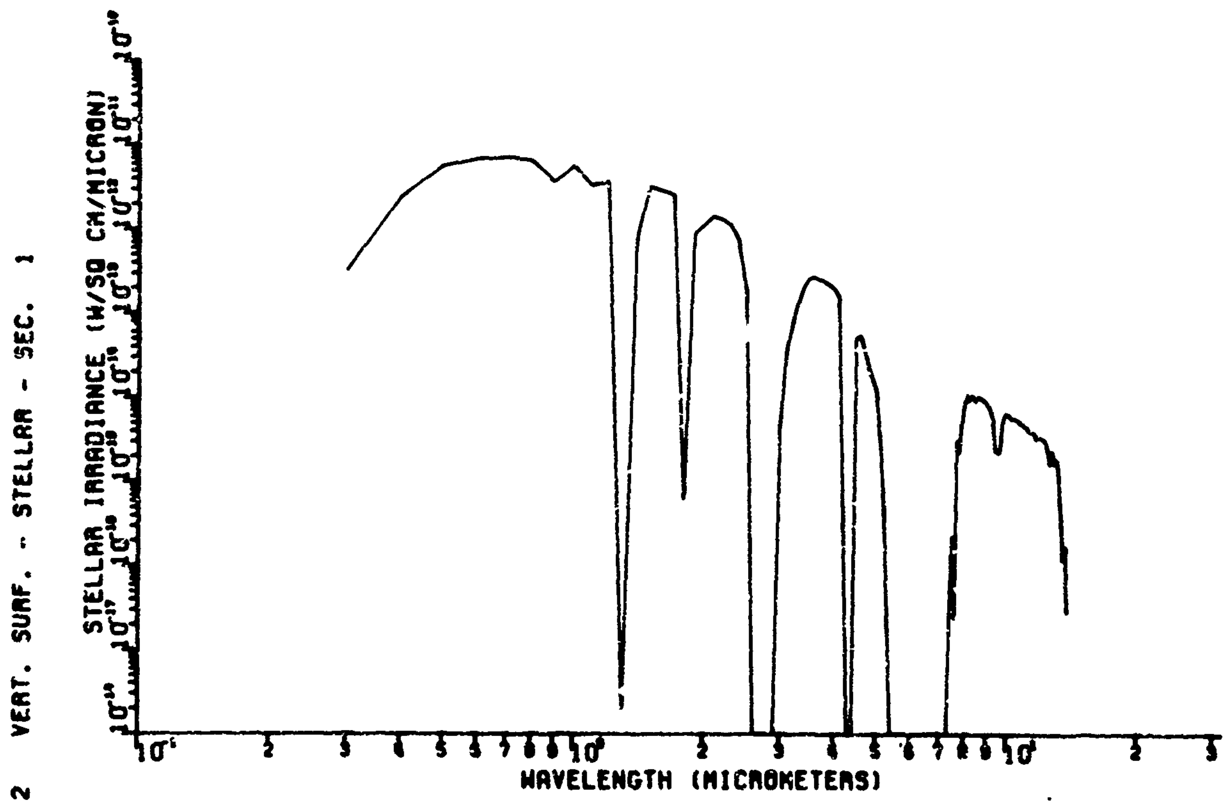


Figure 106. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 1, Zenith Angle of 18.1°

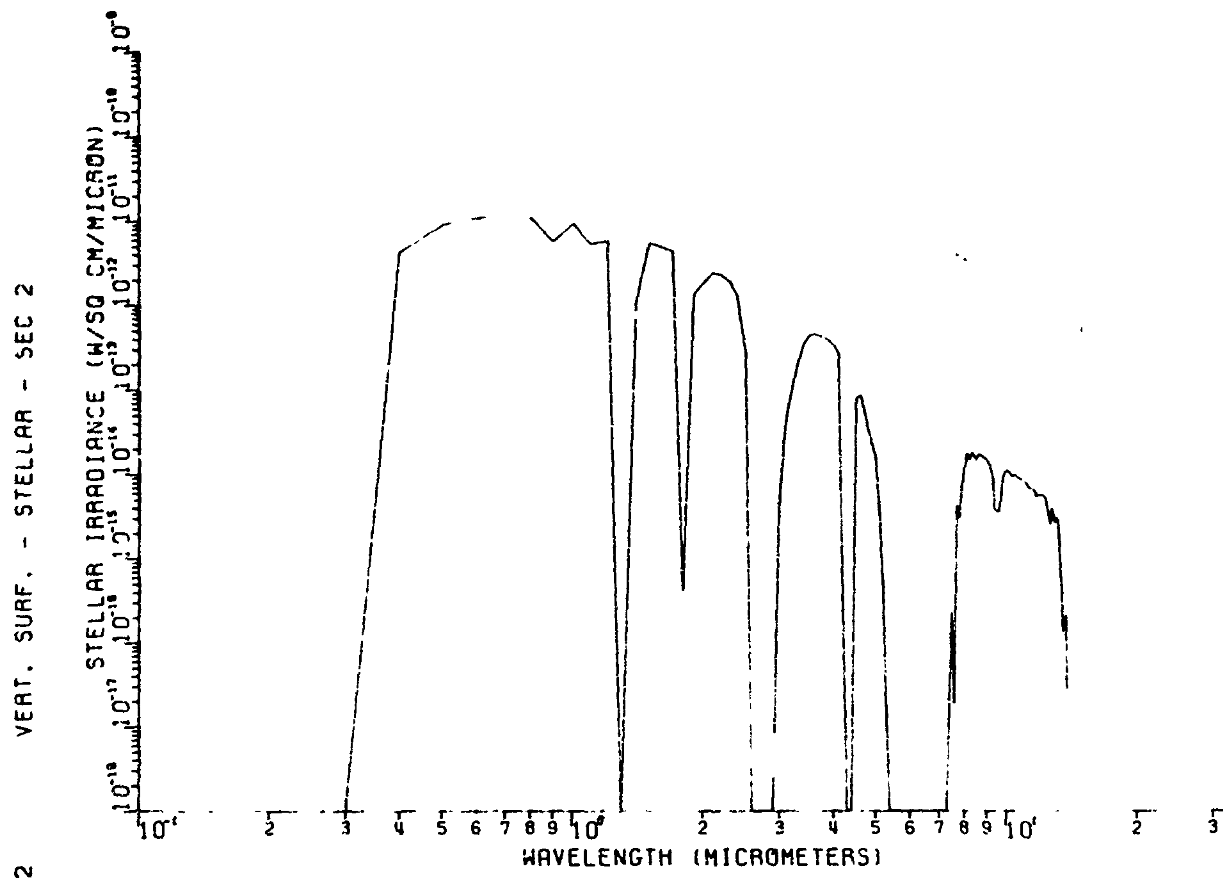


Figure 107. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 2, Zenith Angle of 31.7°

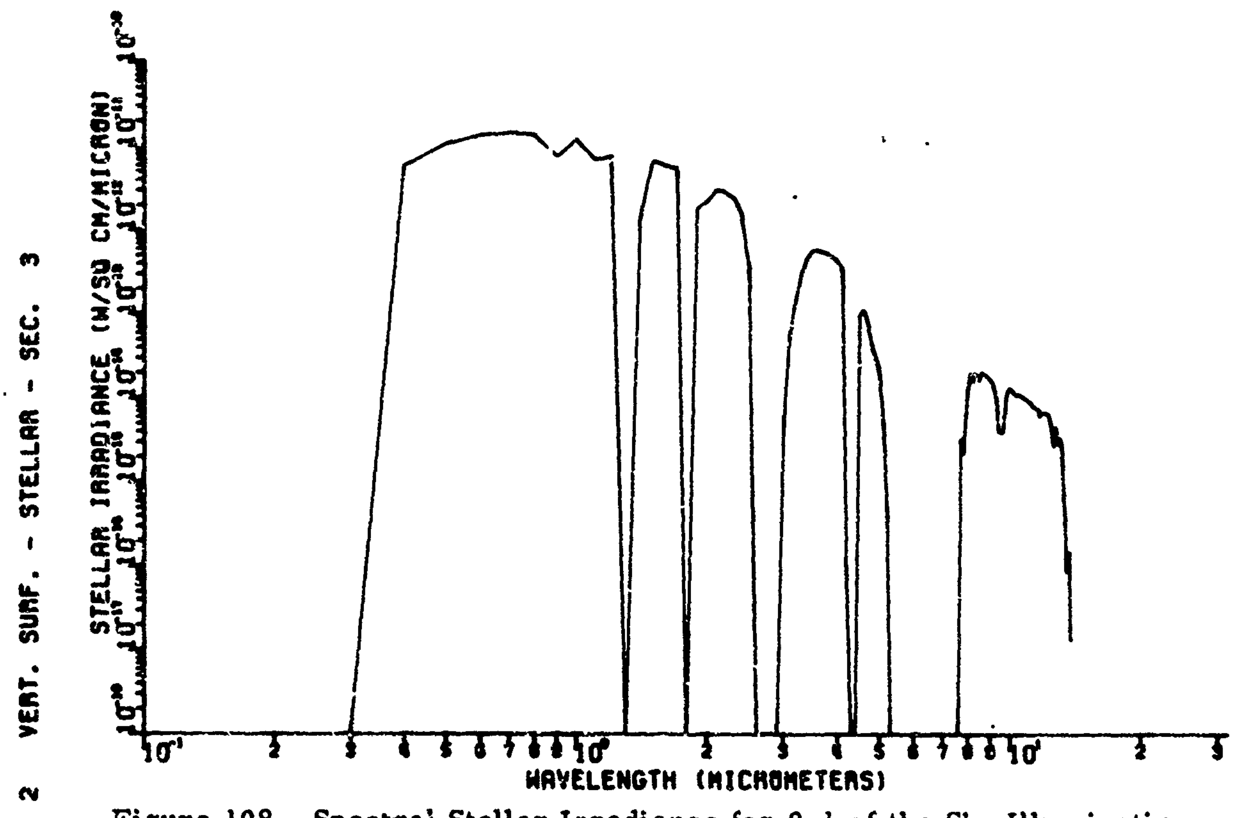


Figure 108. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 3, Zenith Angle of 41.4°

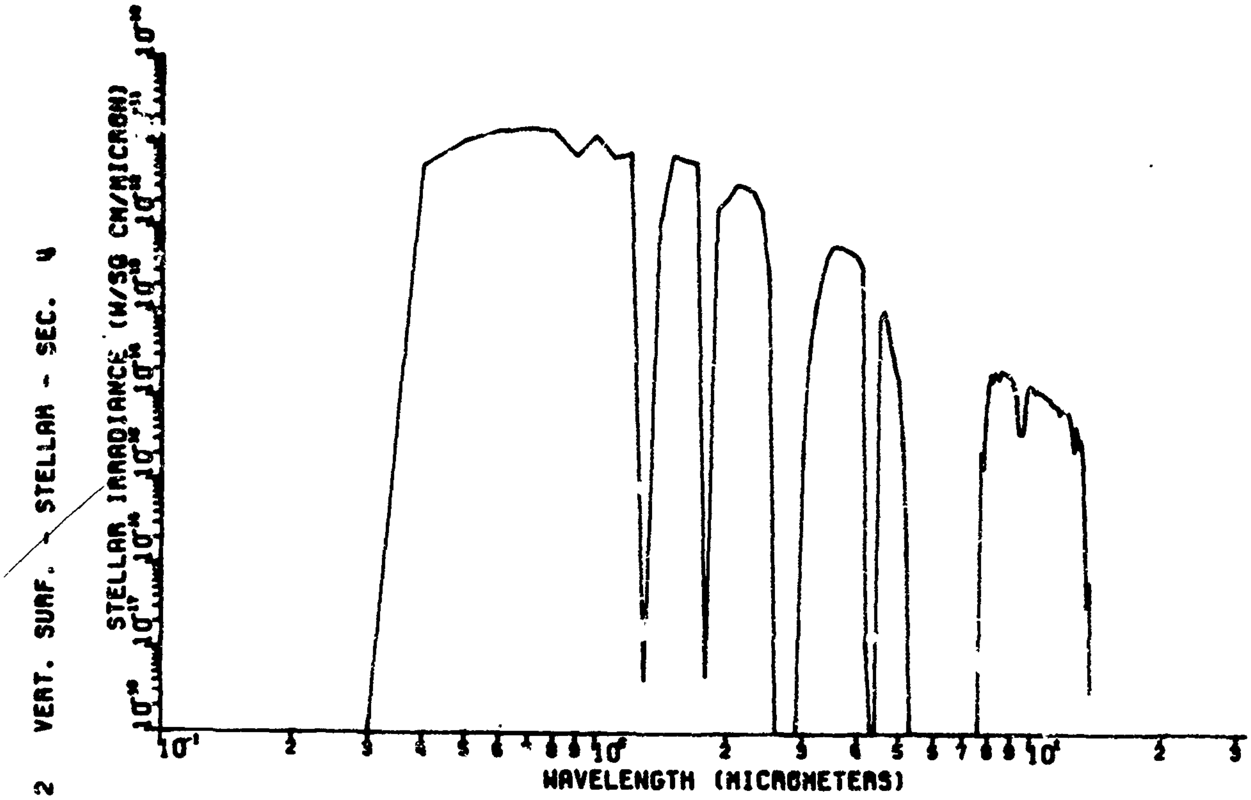


Figure 109. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 4, Zenith Angle of 49.5°

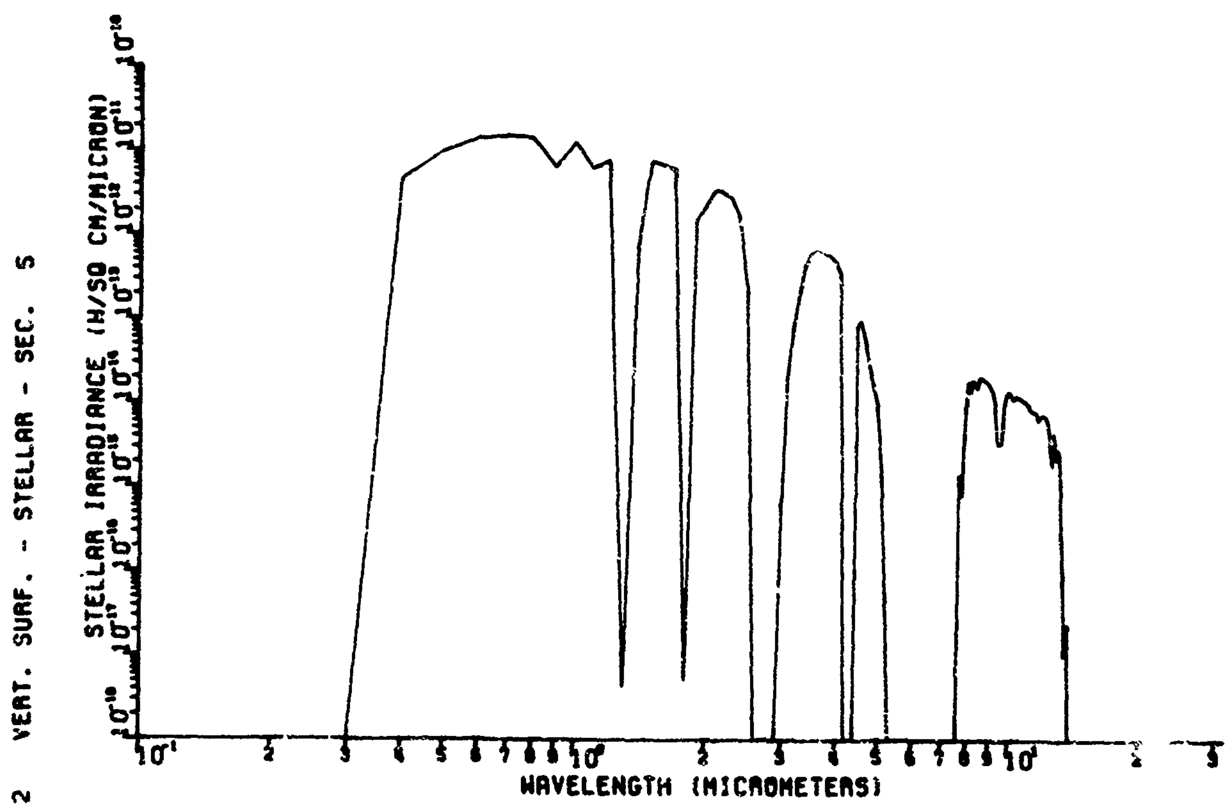


Figure 110. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 5, Zenith Angle of 56.6°

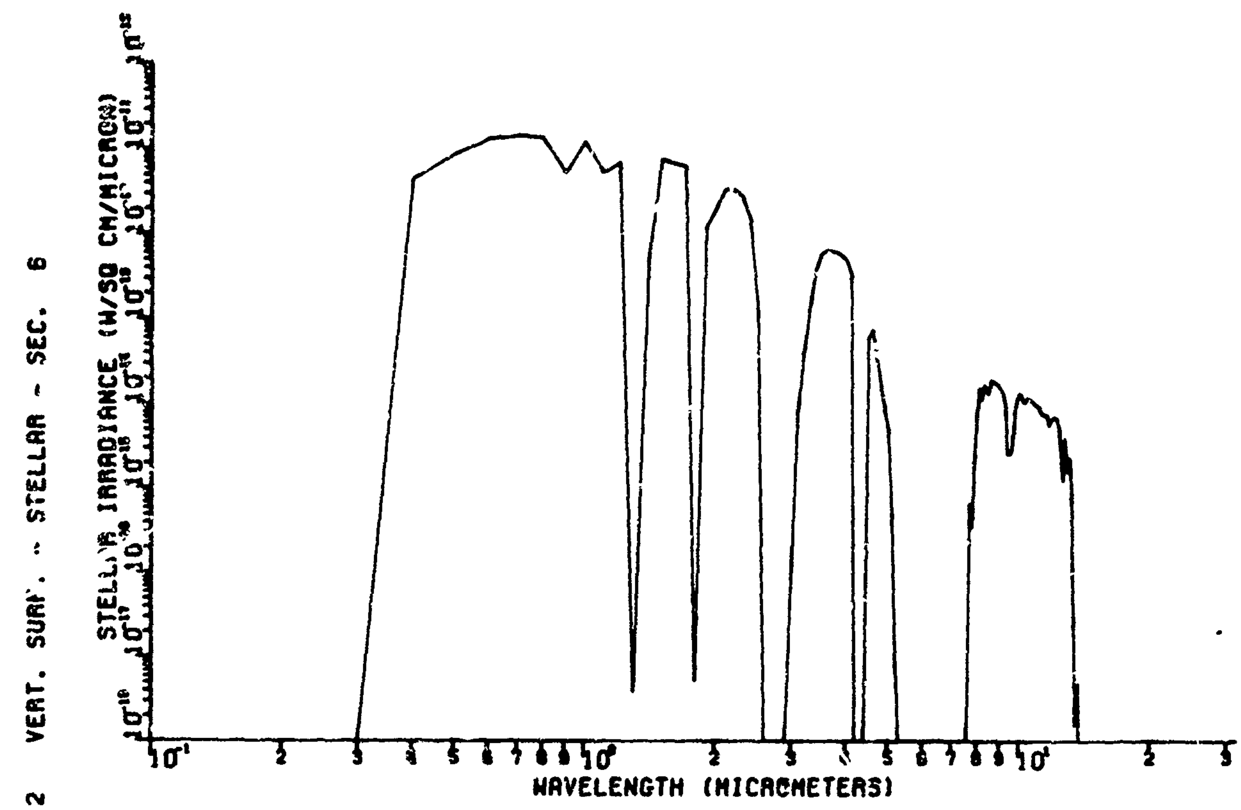


Figure 111. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 6, Zenith Angle of 63.2°

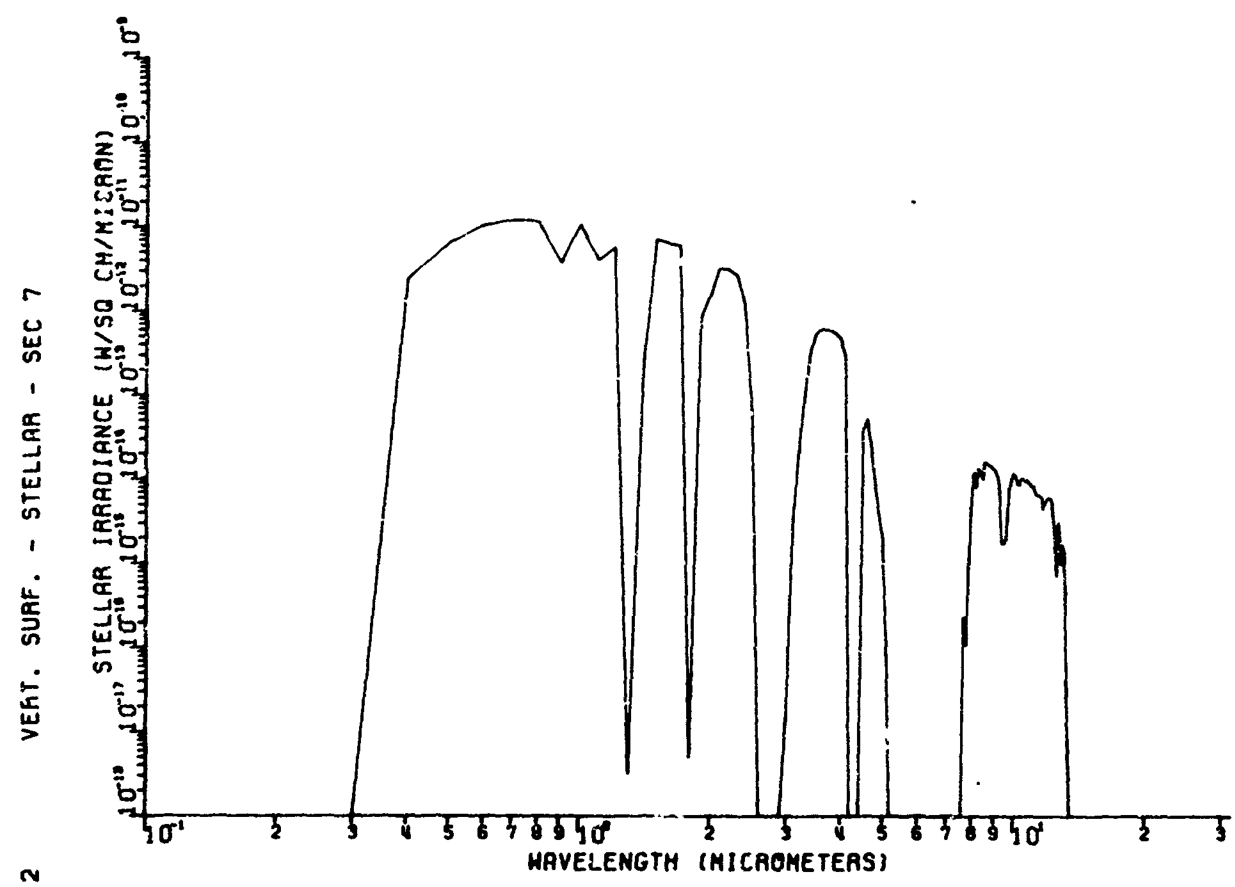


Figure 112. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 7, Zenith Angle of 69.5°

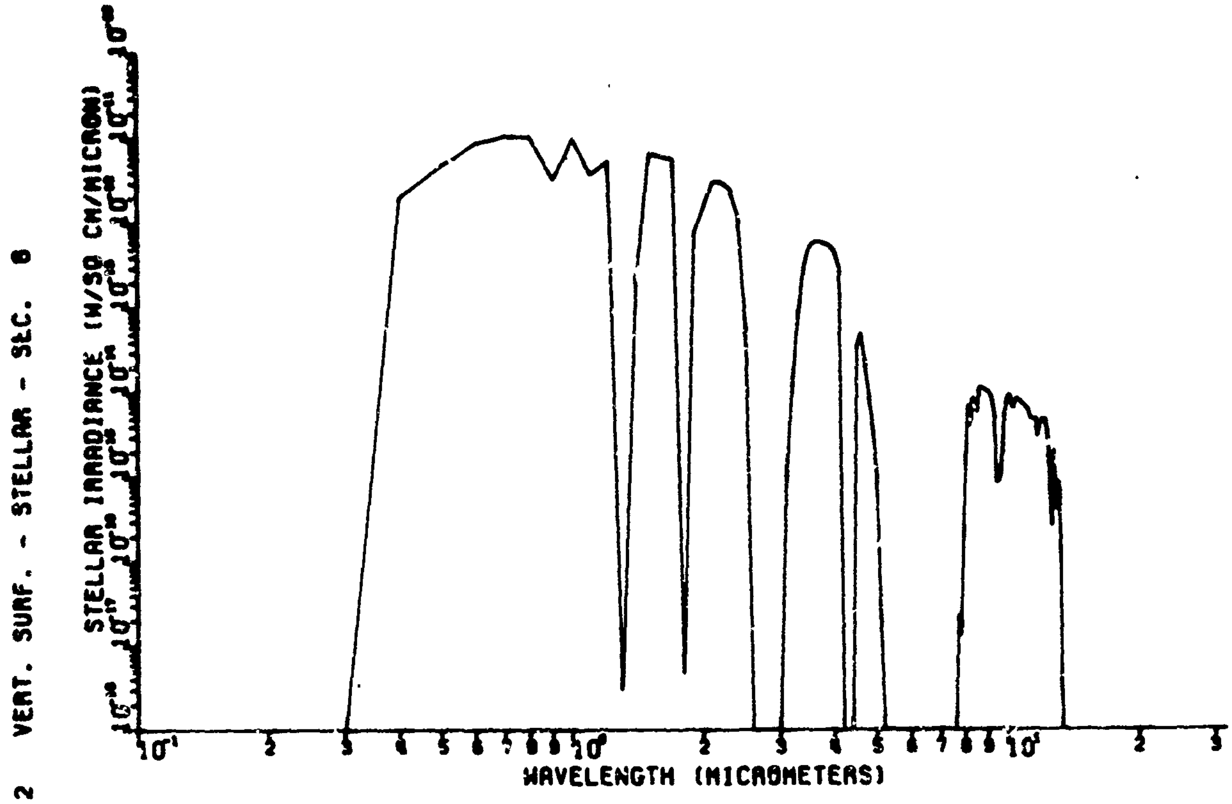


Figure 113. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 8, Zenith Angle of 75.5°

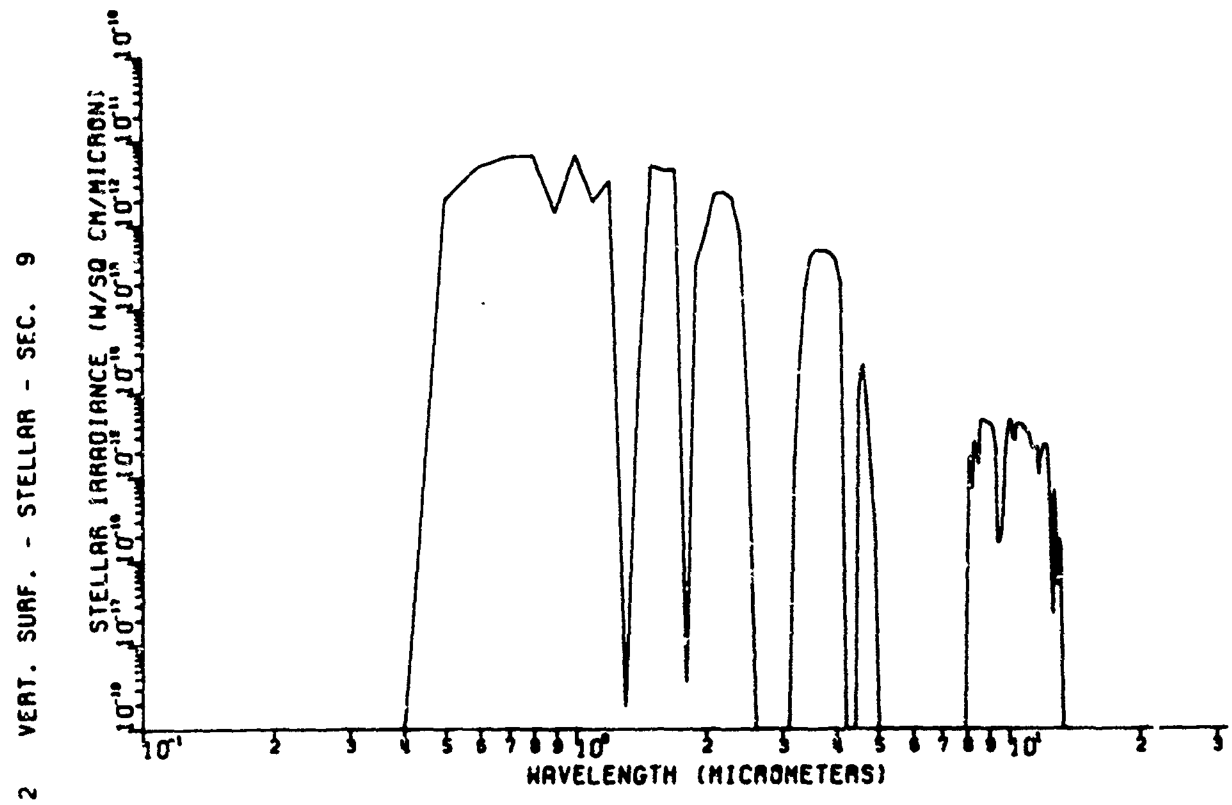


Figure 114. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 9, Zenith Angle of 81.4°

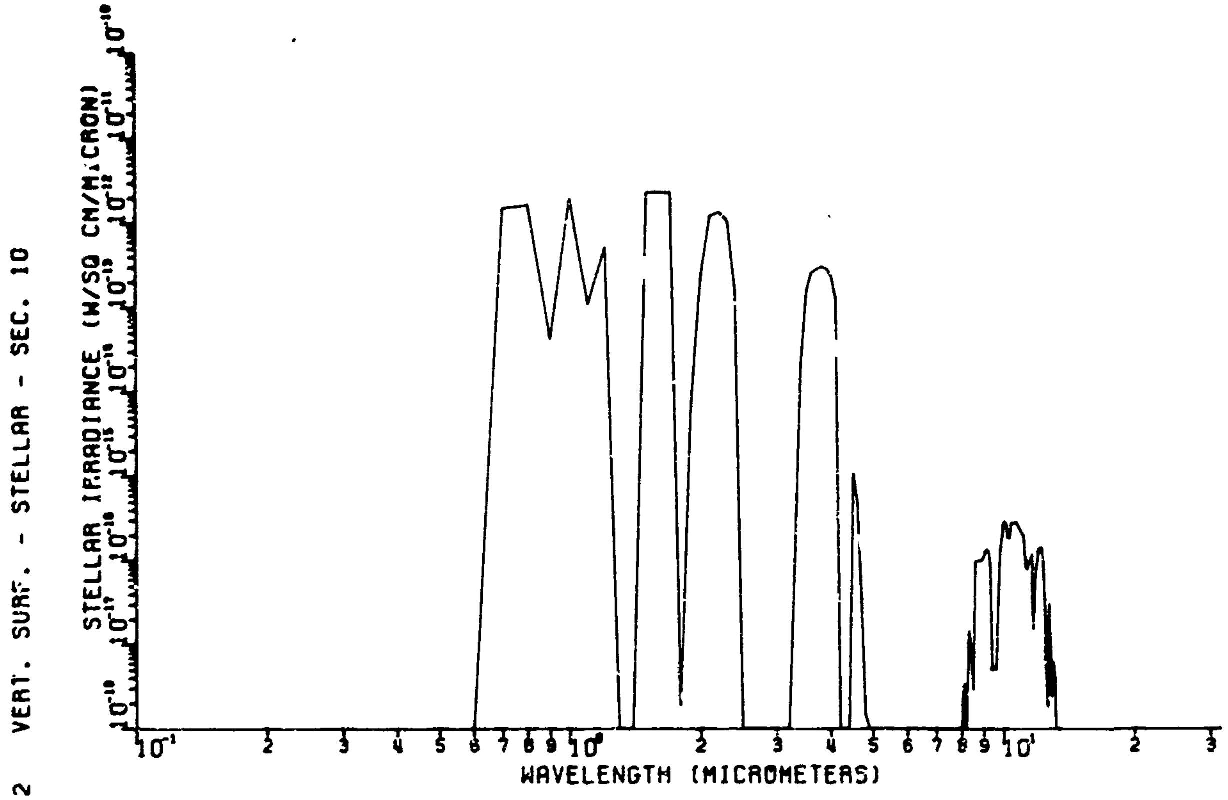


Figure 115. Spectral Stellar Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 10, Zenith Angle of 87.2°

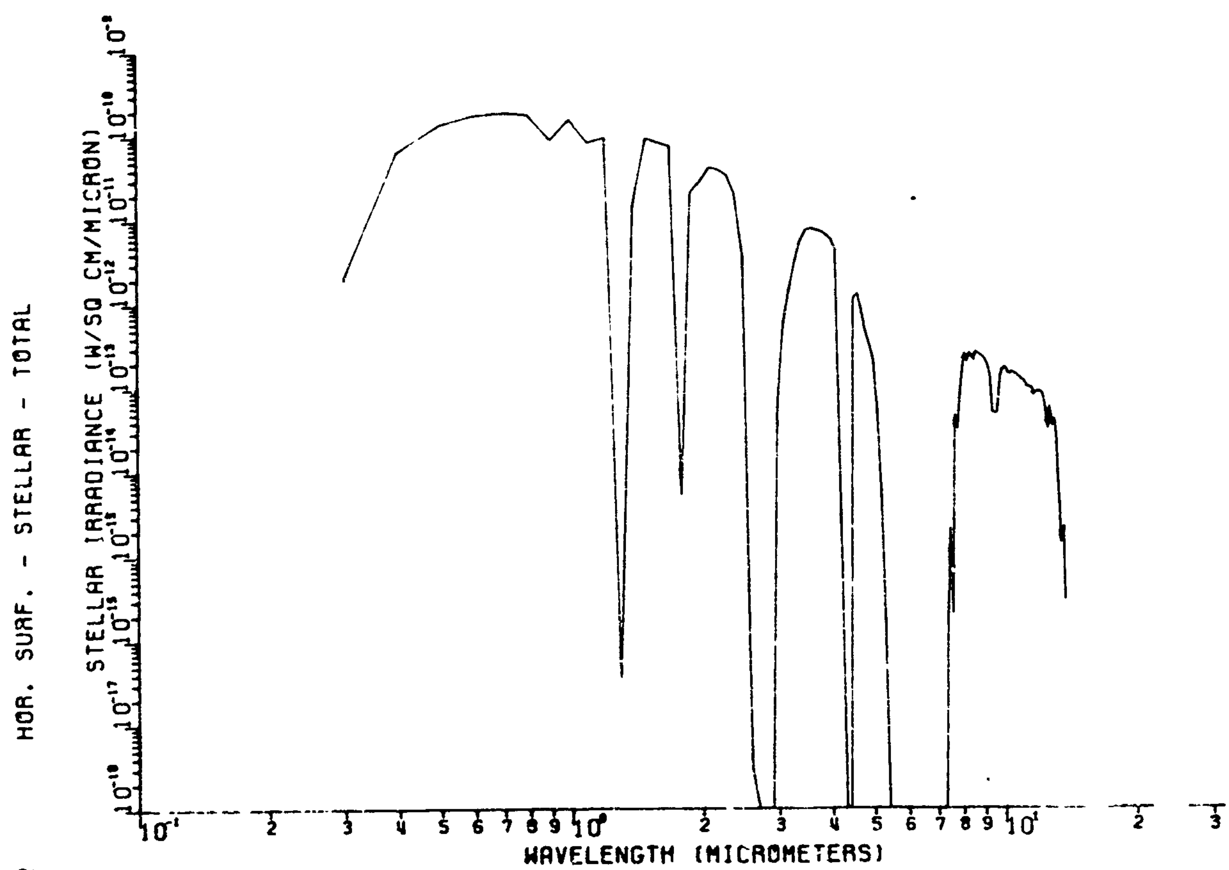


Figure 116. Total Spectral Stellar Irradiance Illuminating a Horizontal Surface

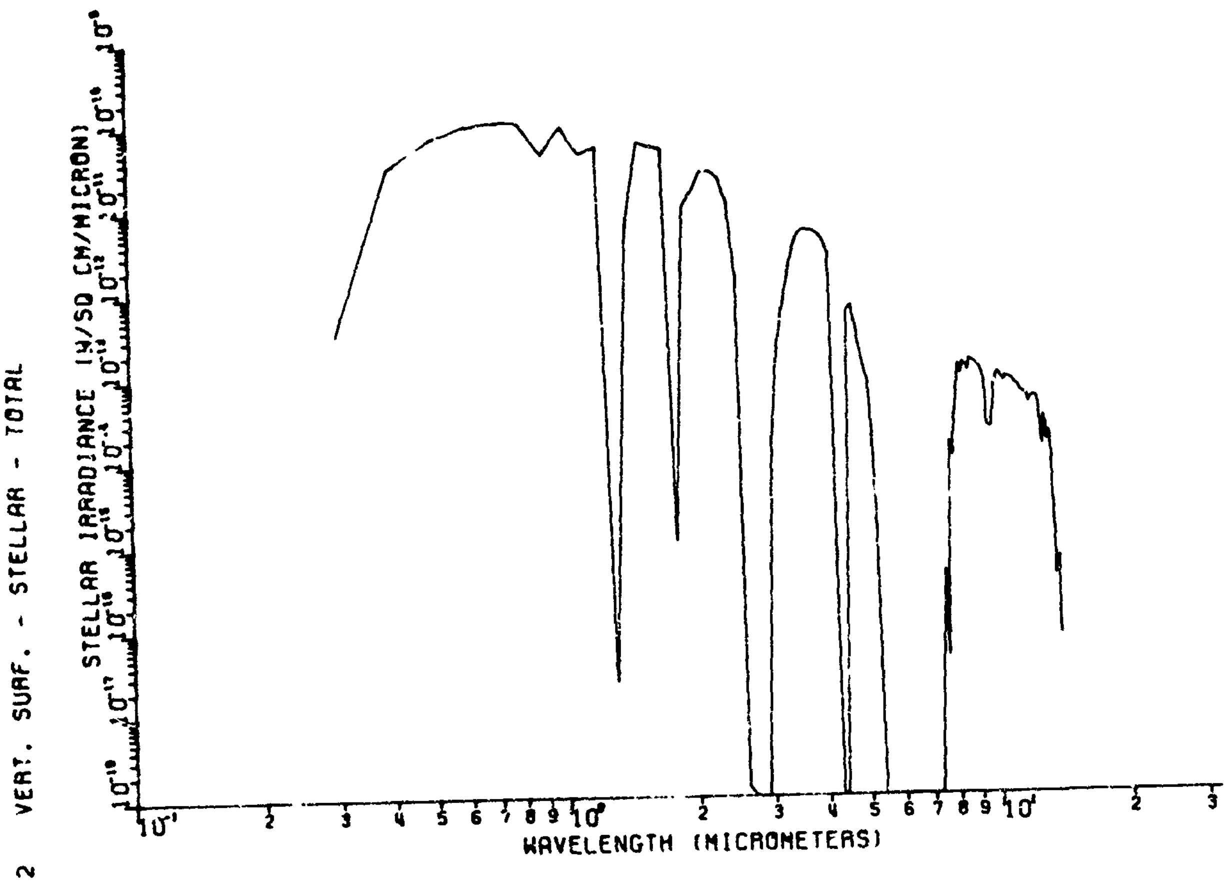


Figure 117. Total Spectral Stellar Irradiance Illuminating a Vertical Surface.

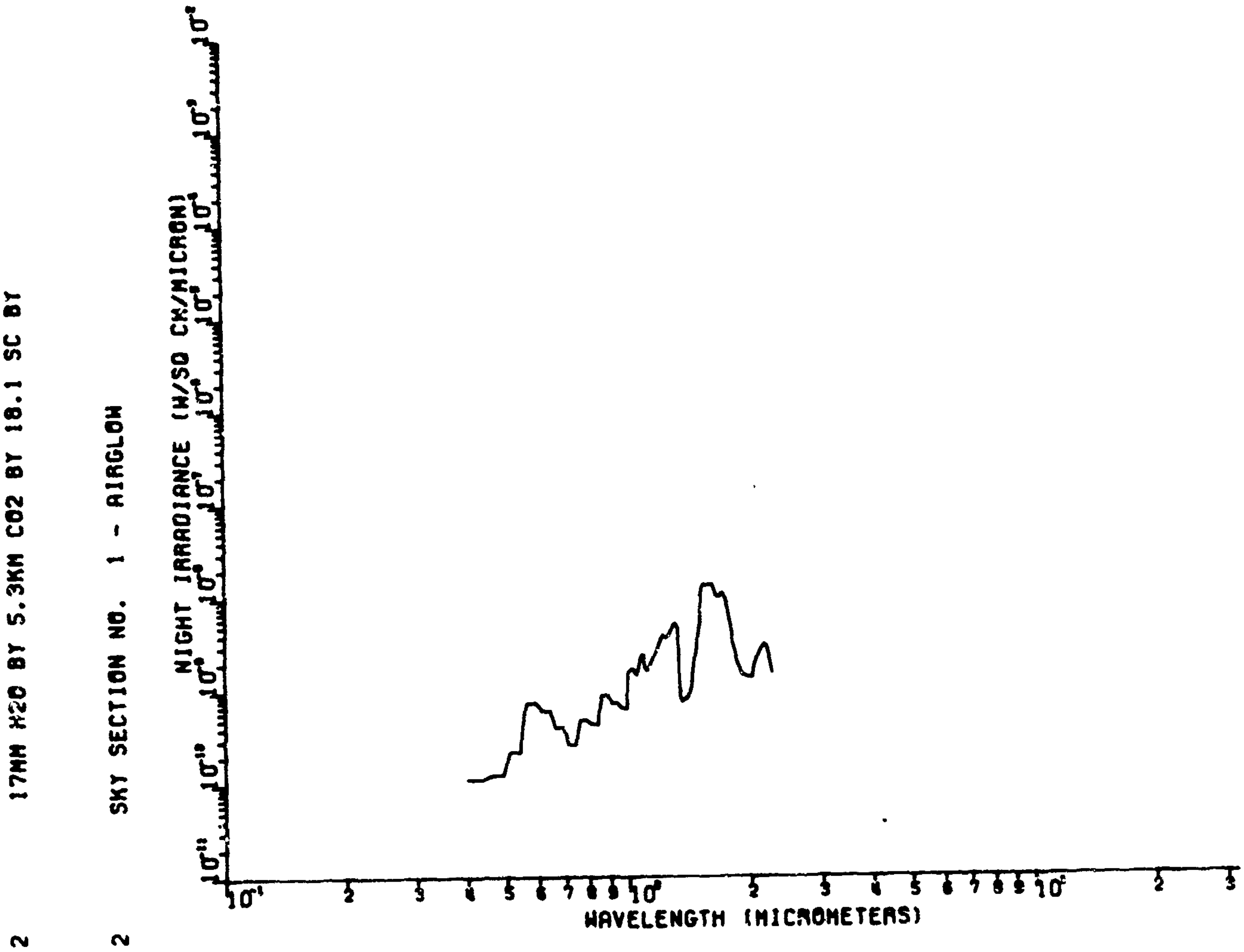


Figure 118. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface, Sky Segment 1, Zenith Angle of 18.1°

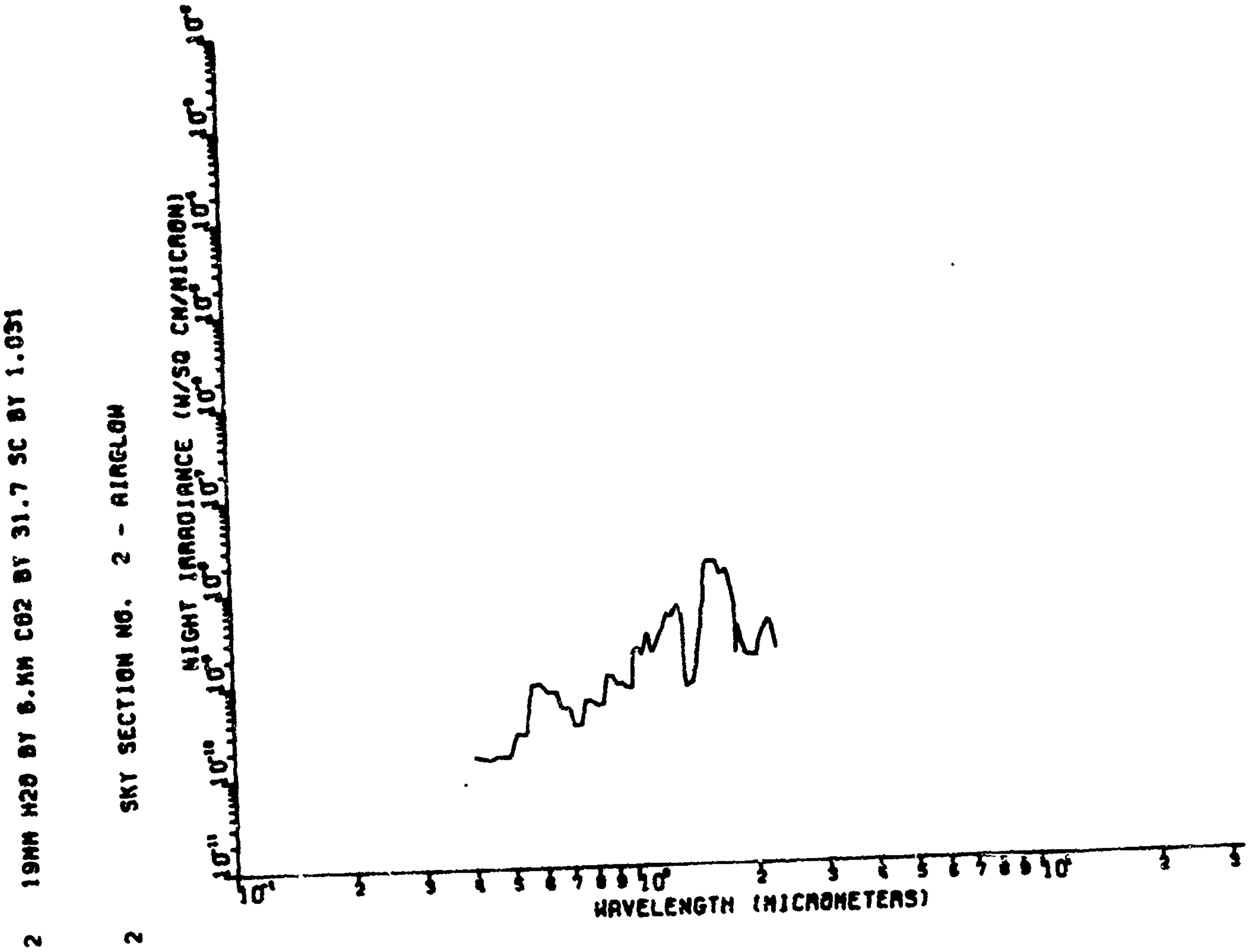


Figure 119. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface, Sky Segment 2, Zenith Angle of 31.7°

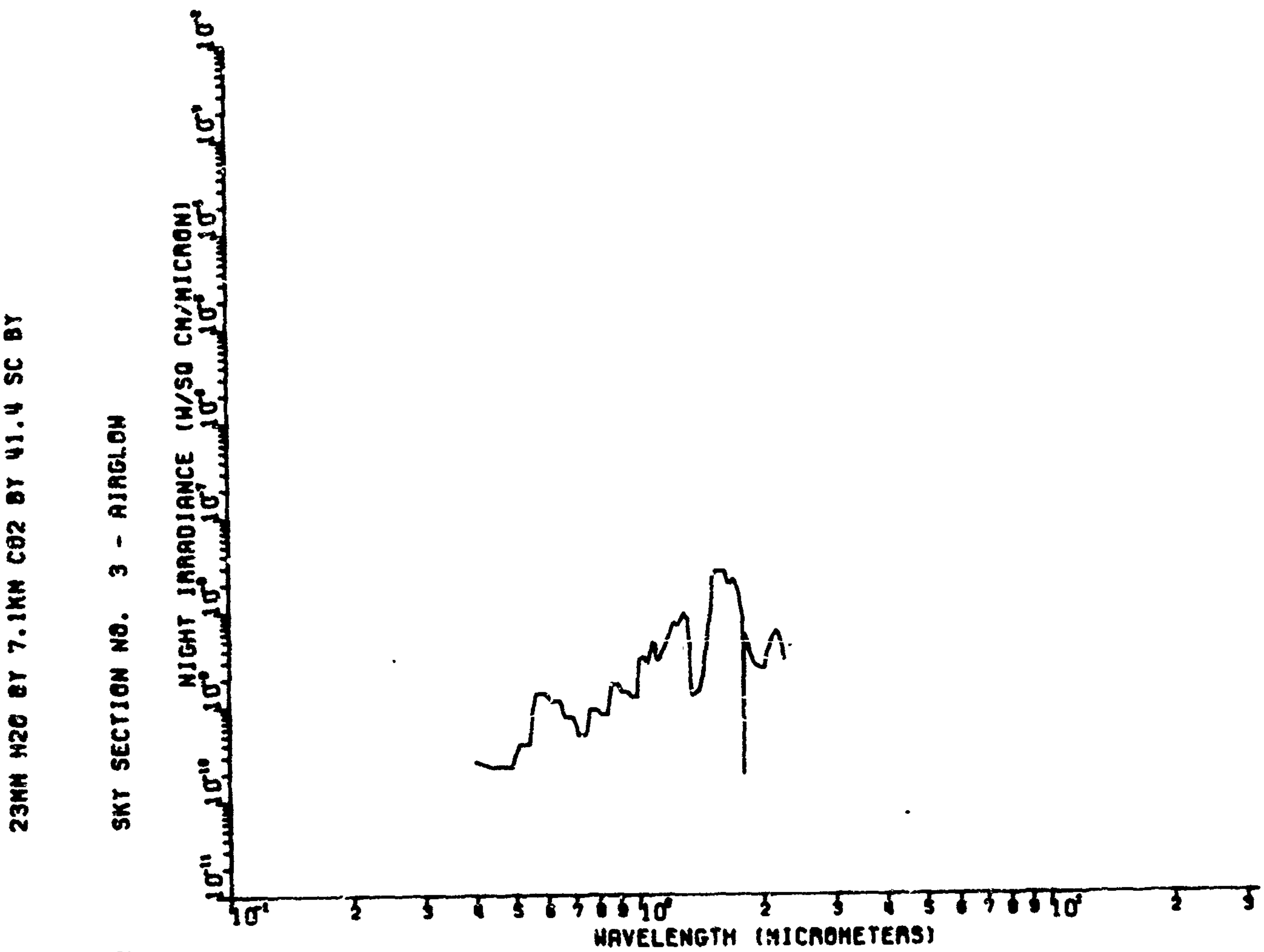


Figure 120. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface, Sky Segment 3, Zenith Angle of 41.4°

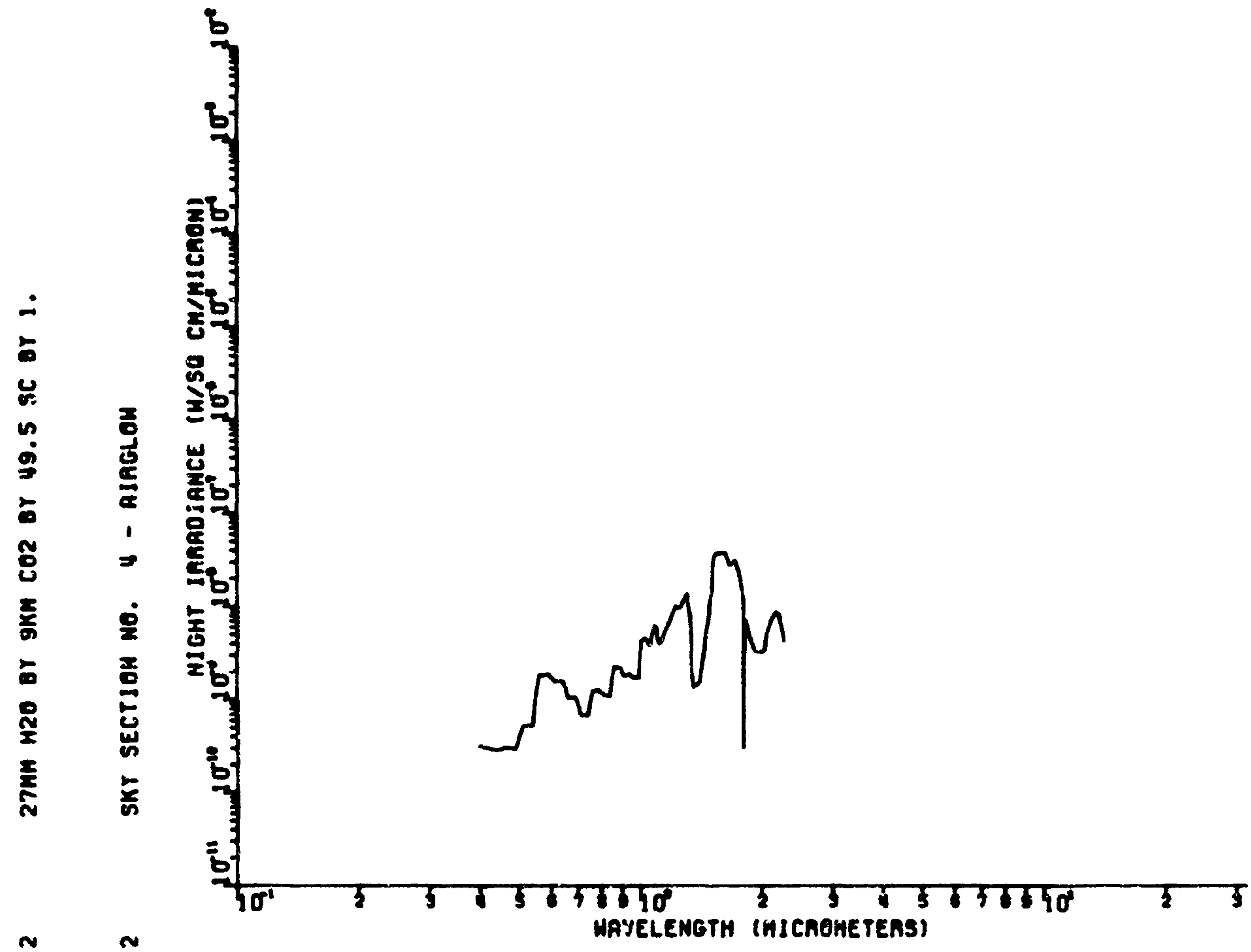


Figure 121. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface Sky Segment 4, Zenith Angle of 49.5°

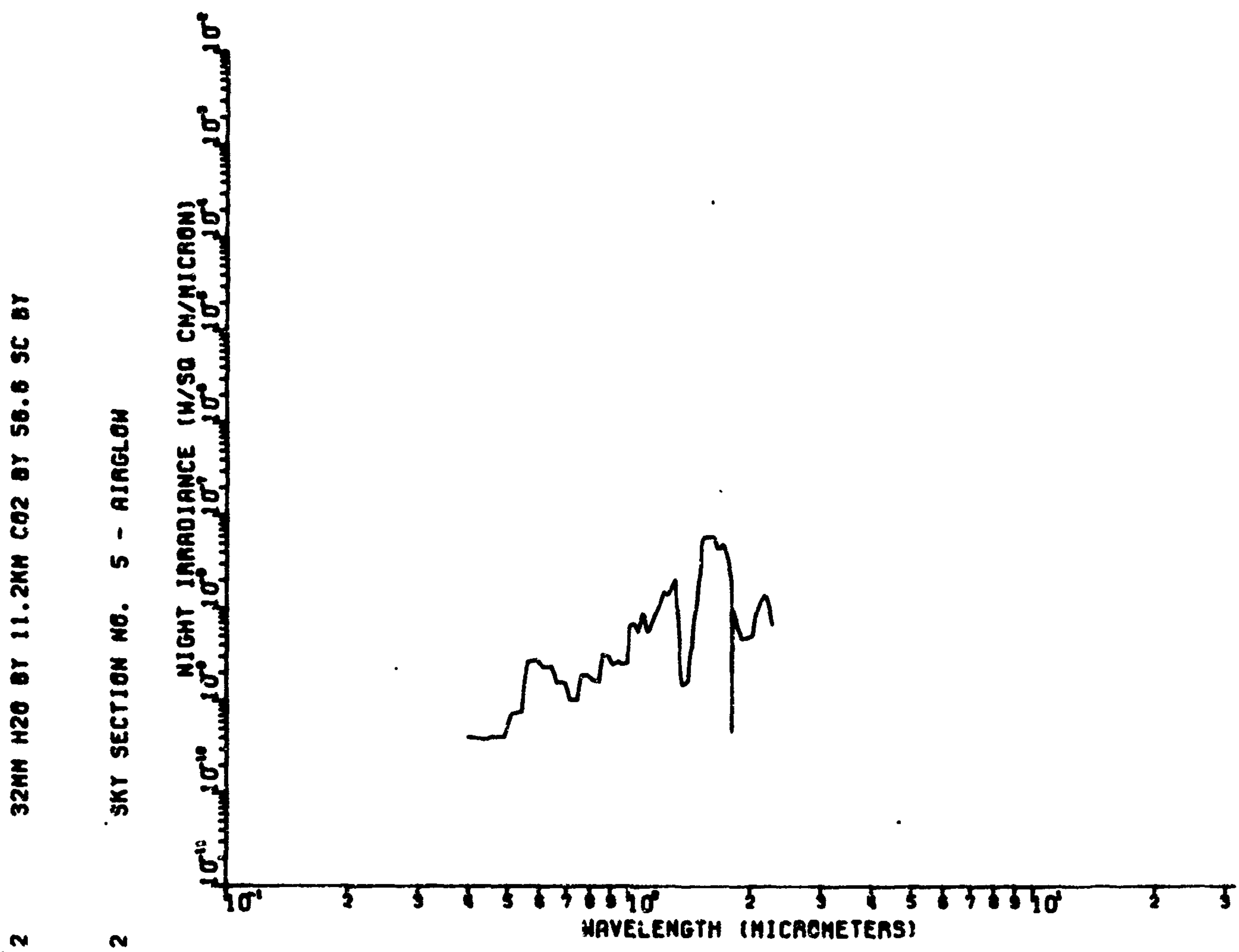


Figure 122. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface Sky Segment 5, Zenith Angle of 56.6°

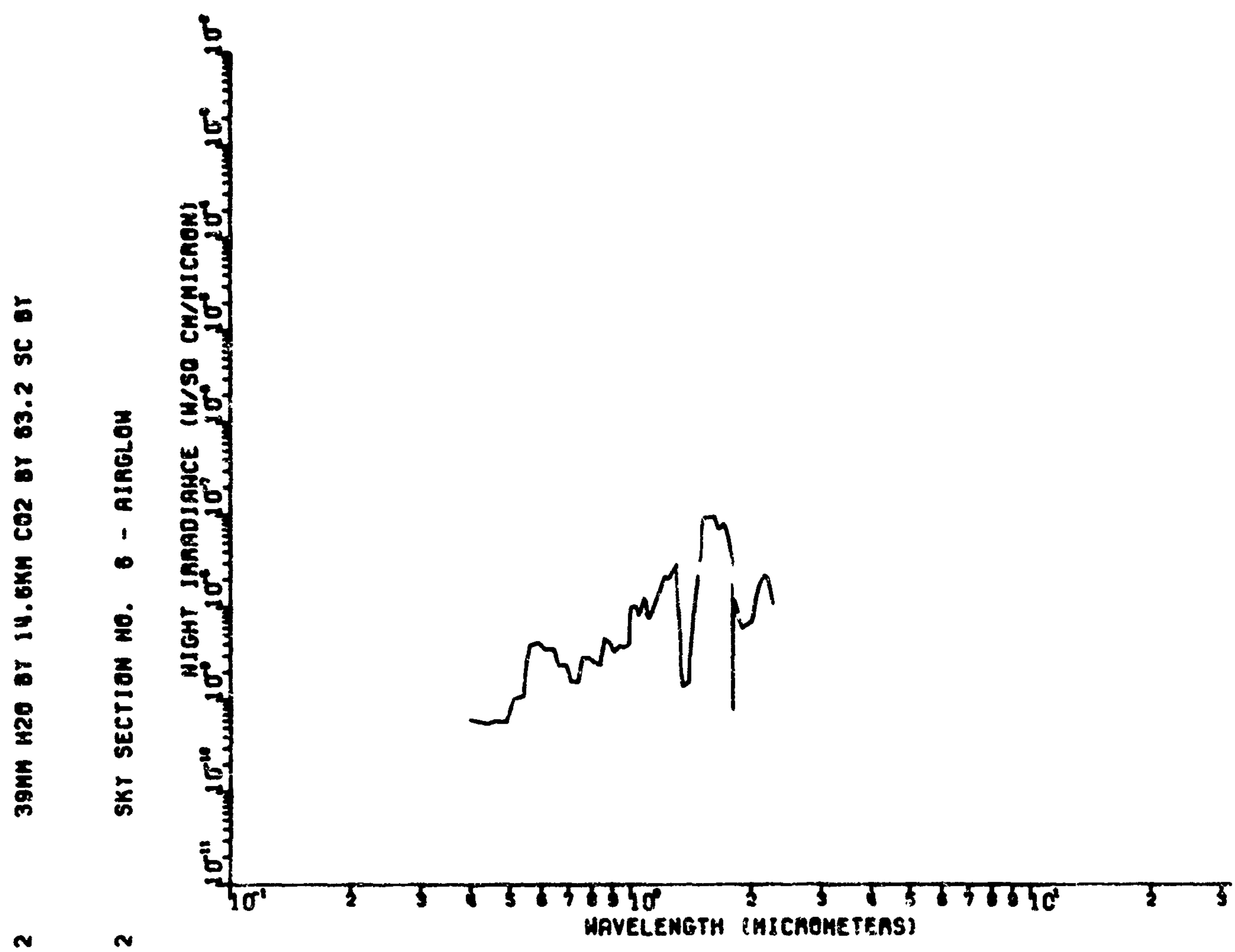


Figure 123. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface Sky Segment 6, Zenith Angle of 63.2°

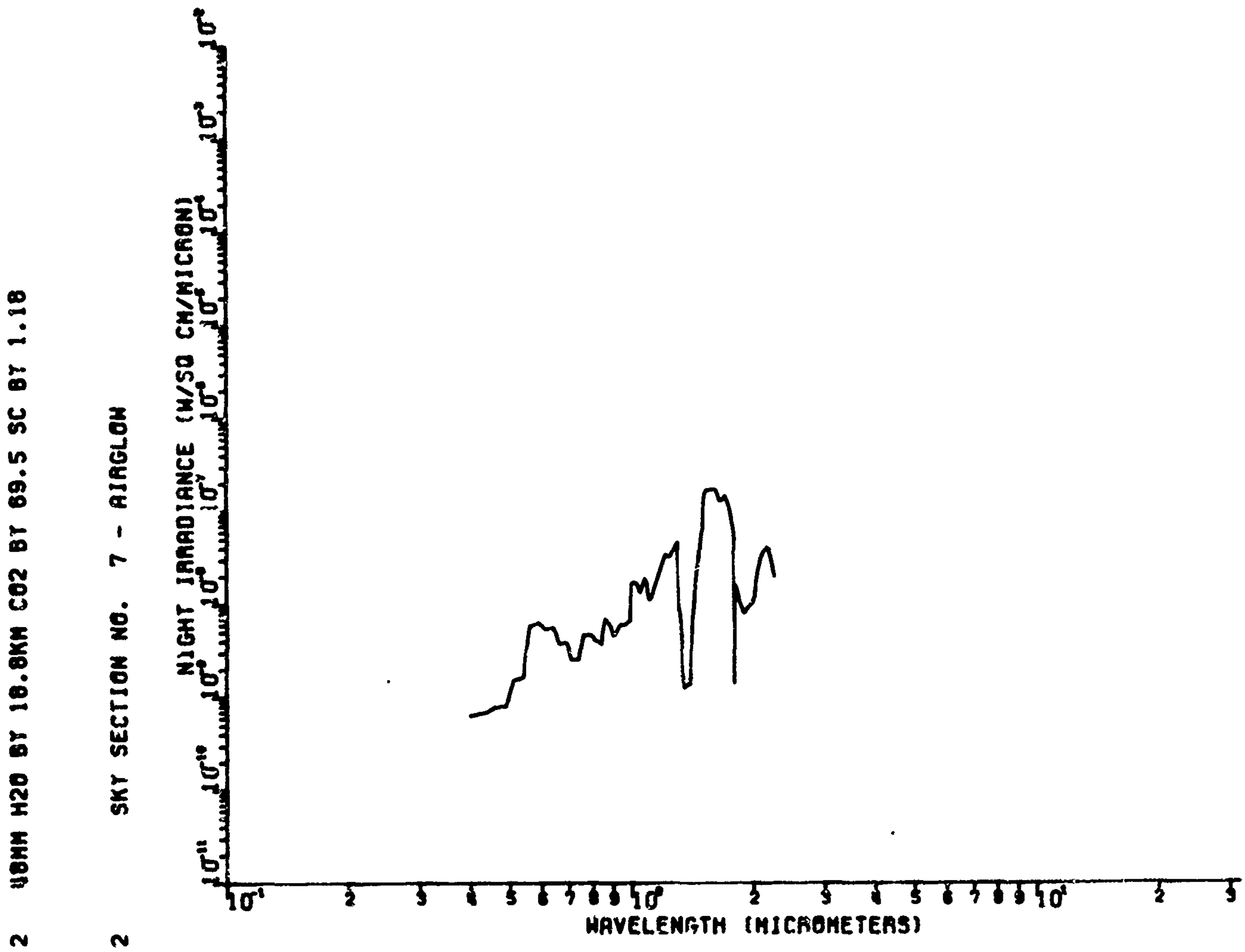


Figure 124. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface Sky Segment 7, Zenith Angle of 69.5°

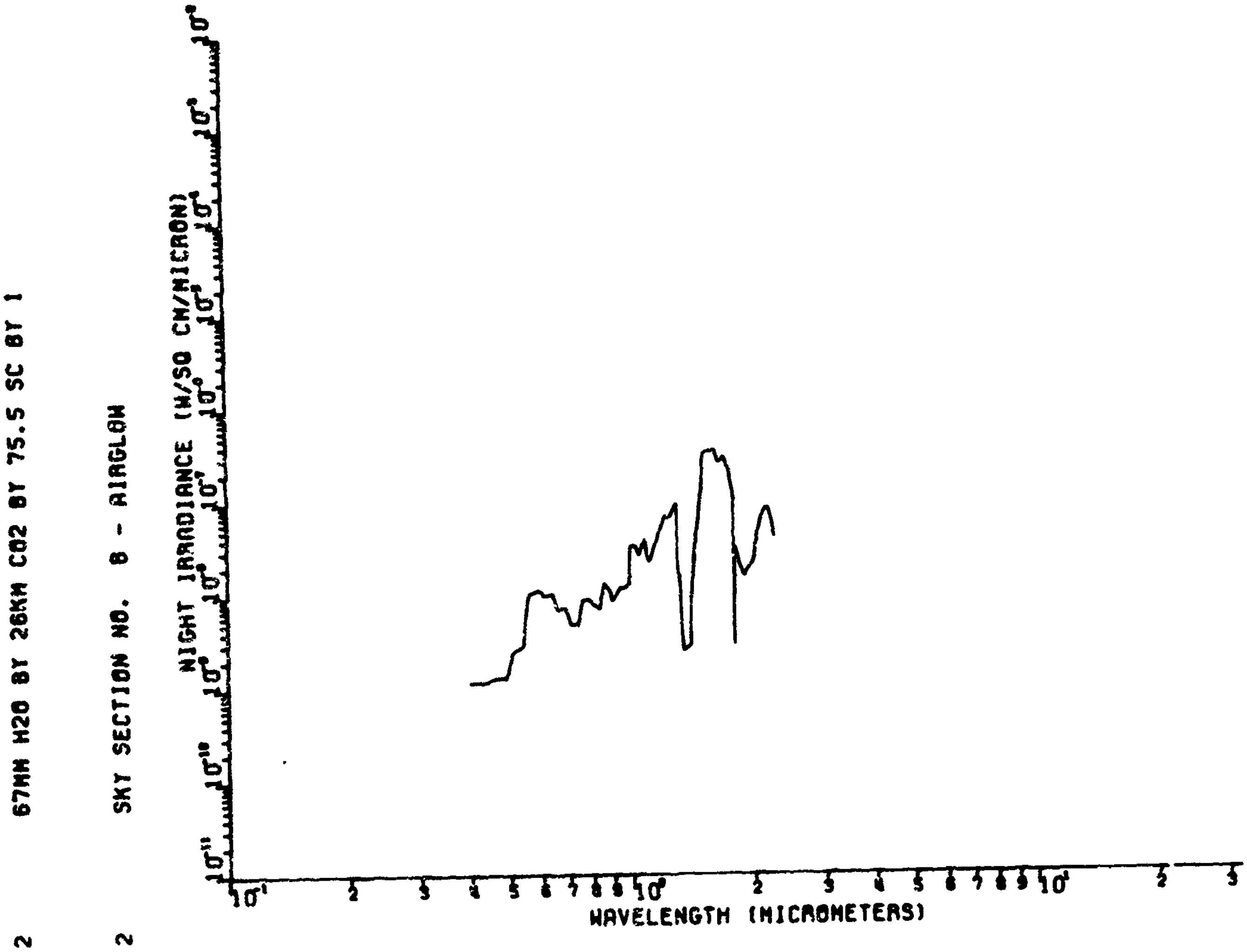


Figure 125. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface, Sky Segment 8, Zenith Angle of 75.5°

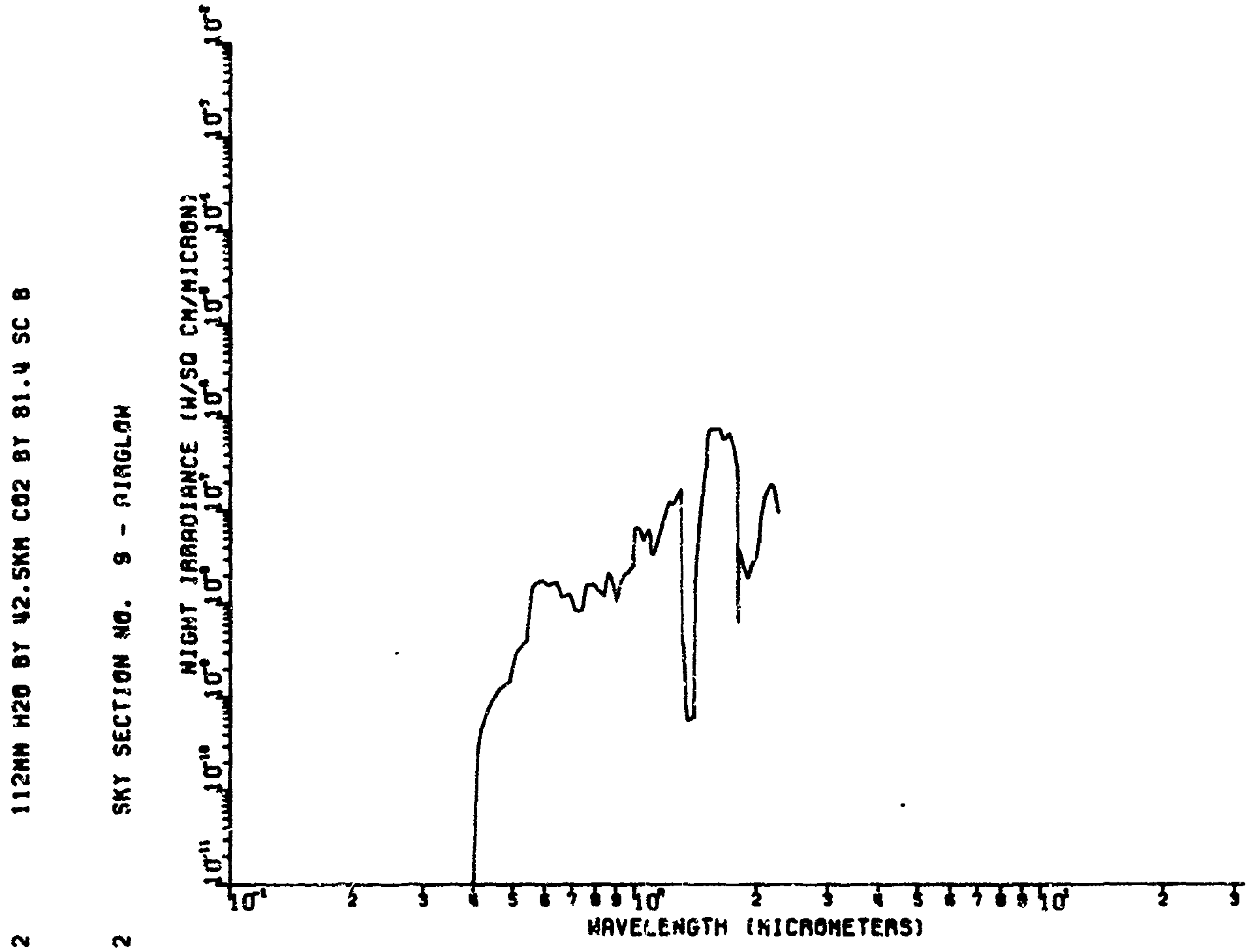


Figure 126. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface Sky Segment 9, Zenith Angle of 81.4°

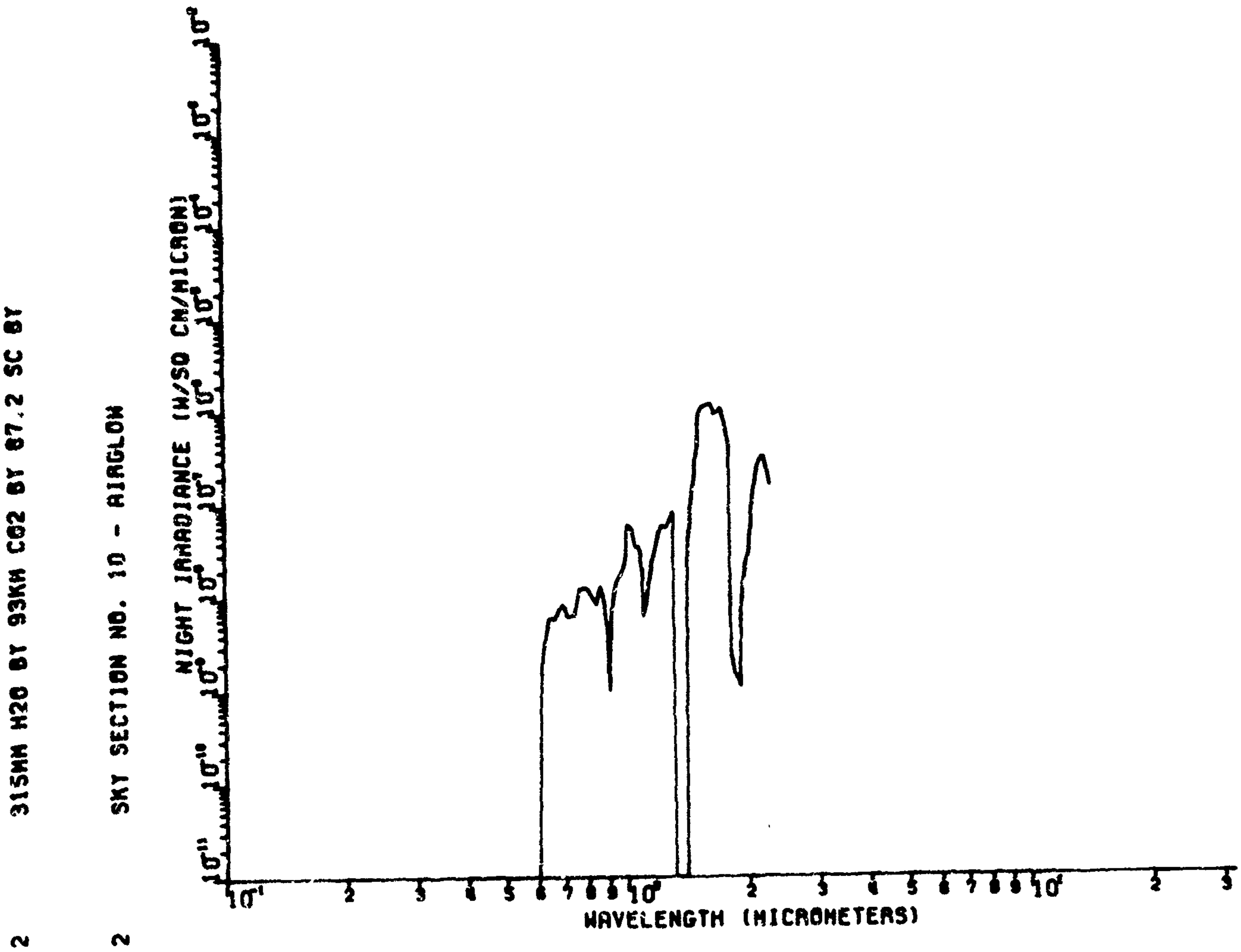


Figure 127. Spectral Nightglow Irradiance for 0.1 of the Sky at the Surface Sky Segment 10, Zenith Angle of 87.2°

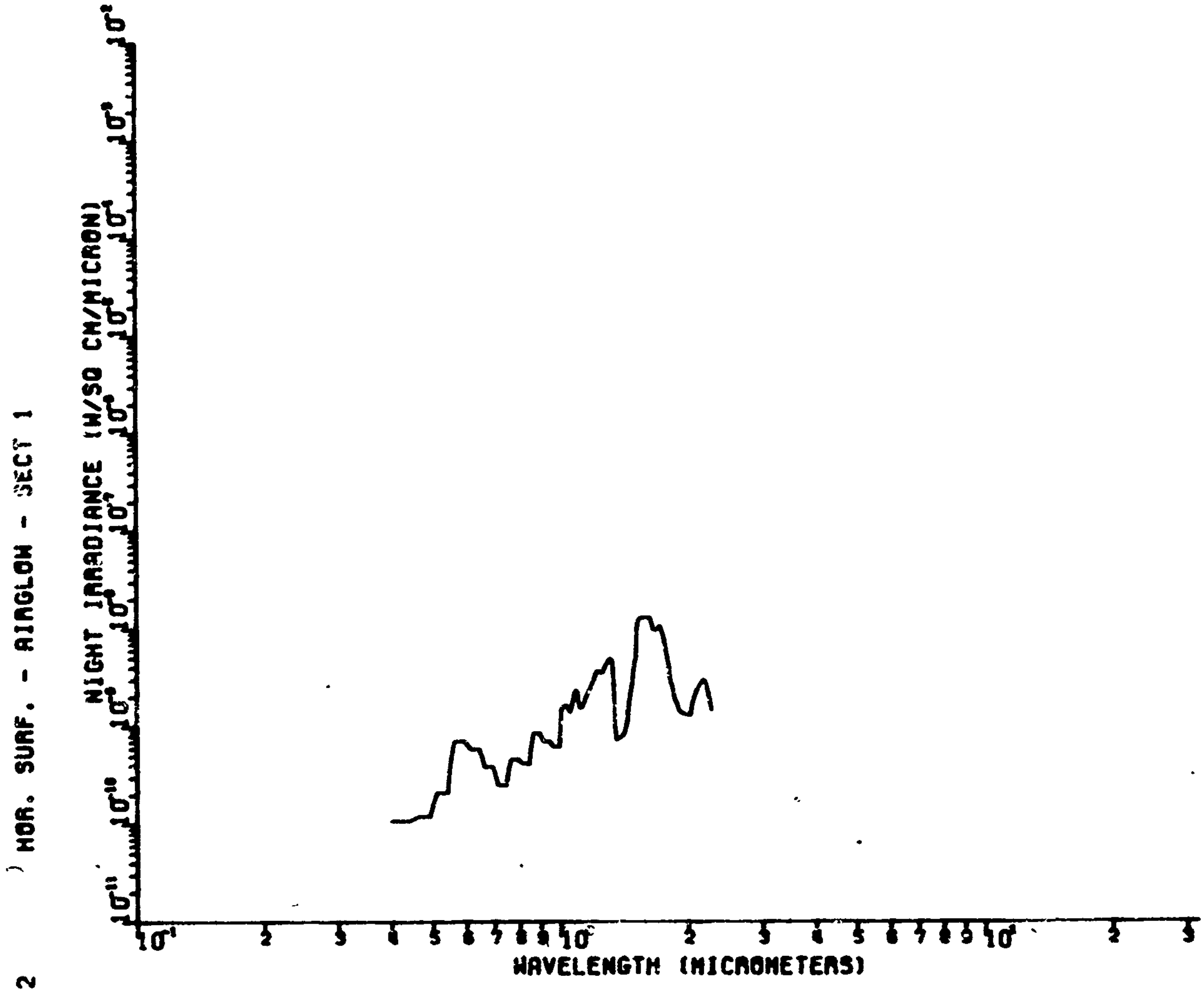


Figure 128. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 1, Zenith Angle of 18.1°

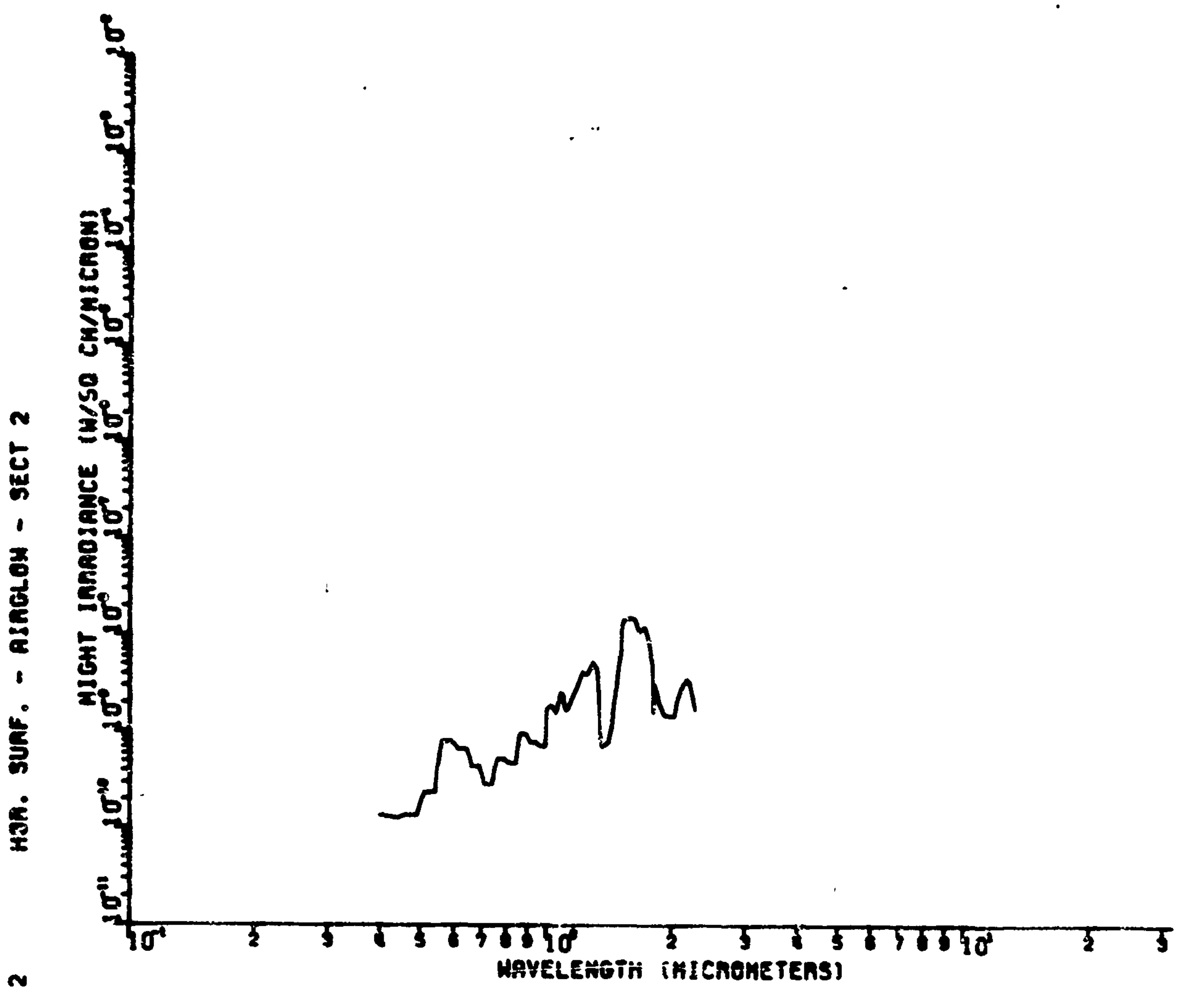


Figure 129. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 2, Zenith Angle of 31.7°

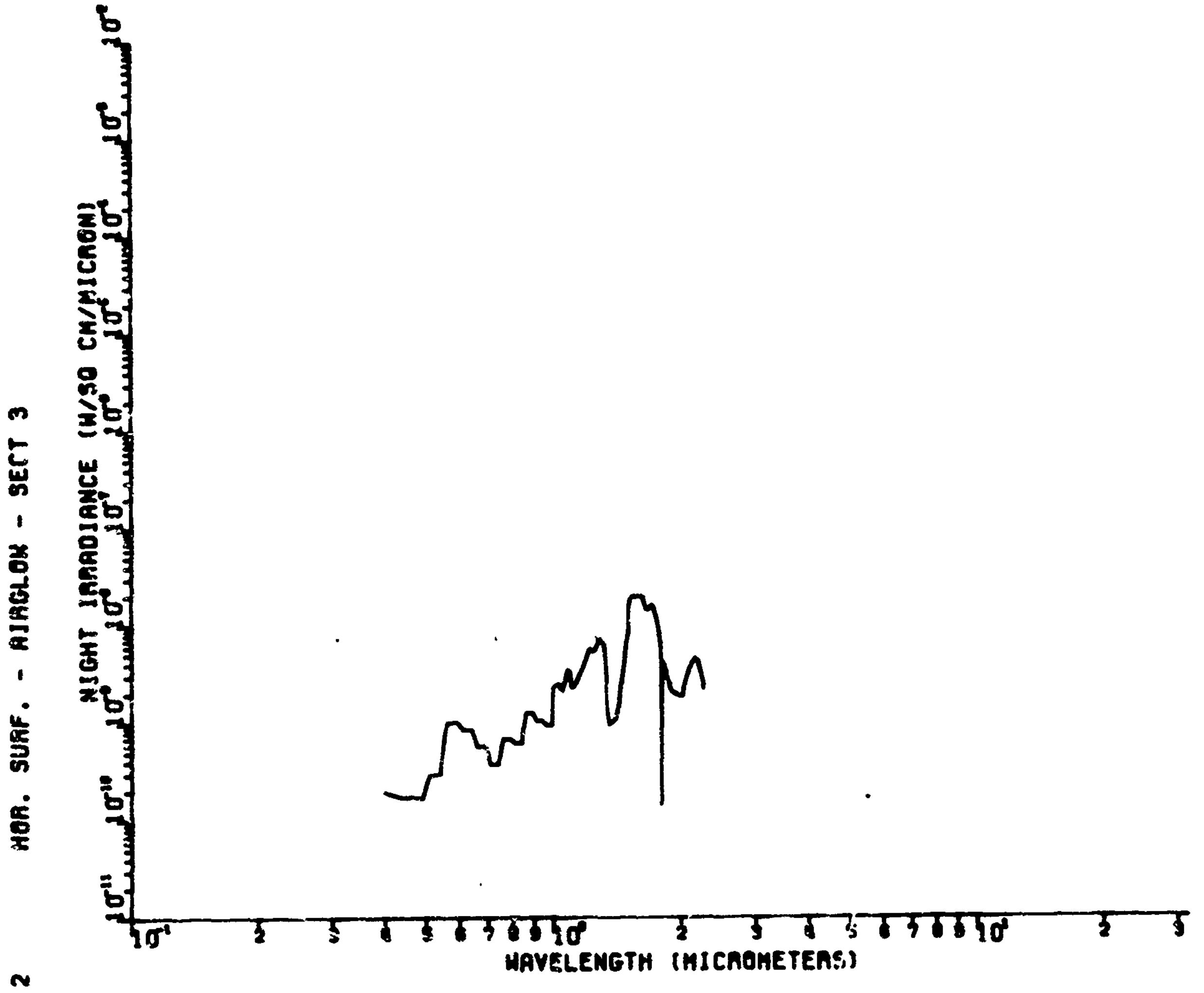


Figure 130. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 3, Zenith Angle of 41.4°

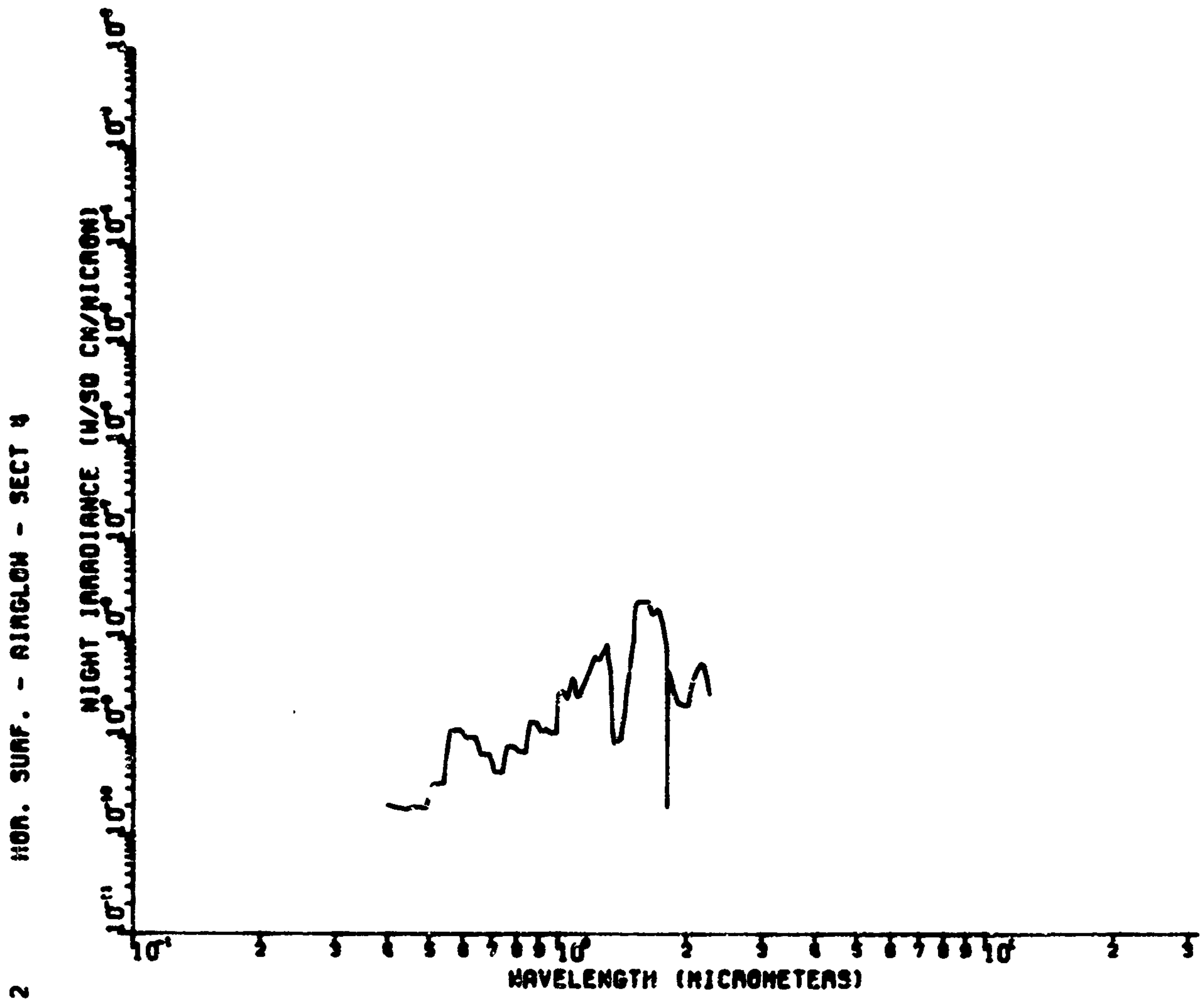


Figure 131. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 4, Zenith Angle of 49.5°

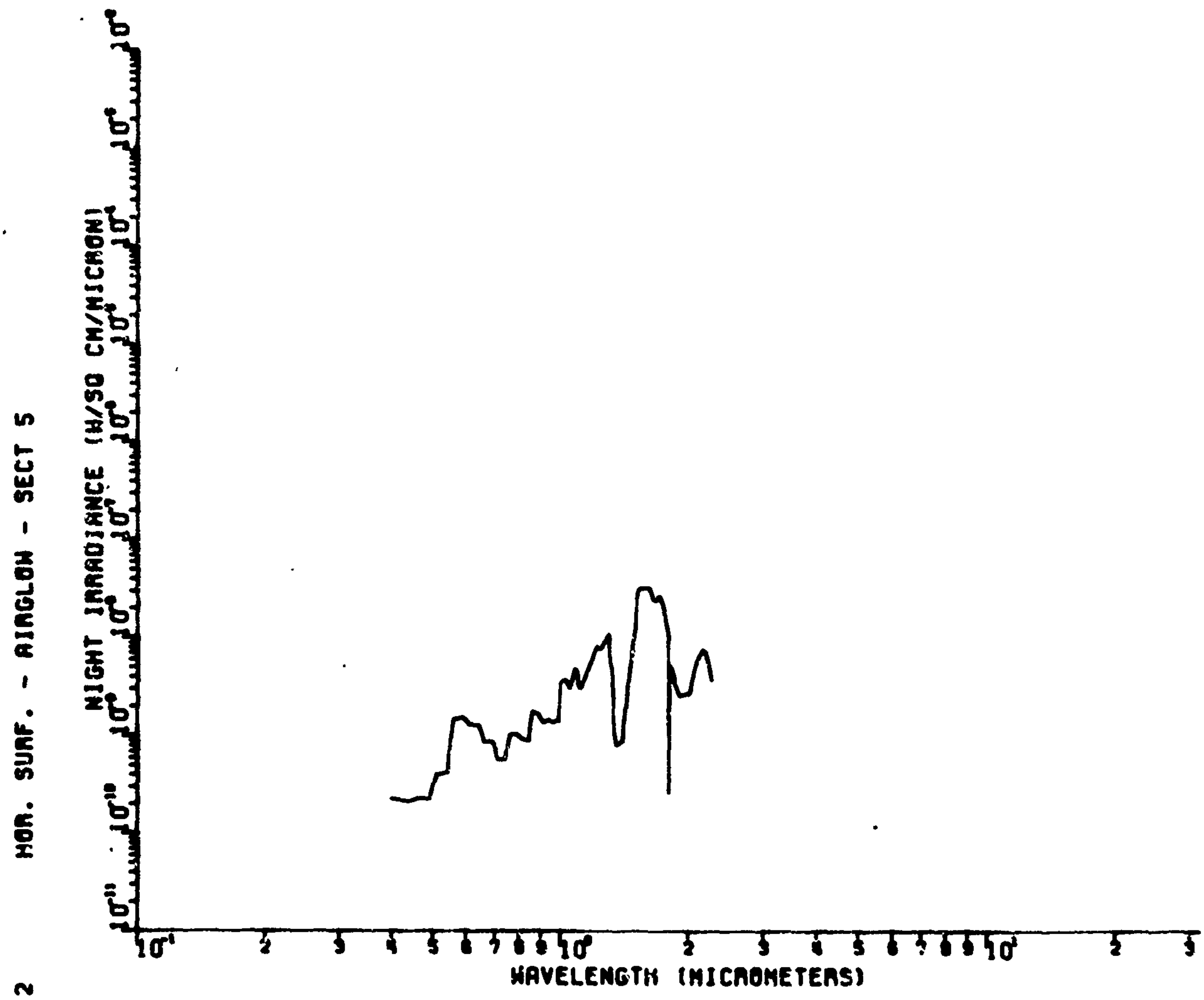


Figure 132. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 5, Zenith Angle of 56.6°

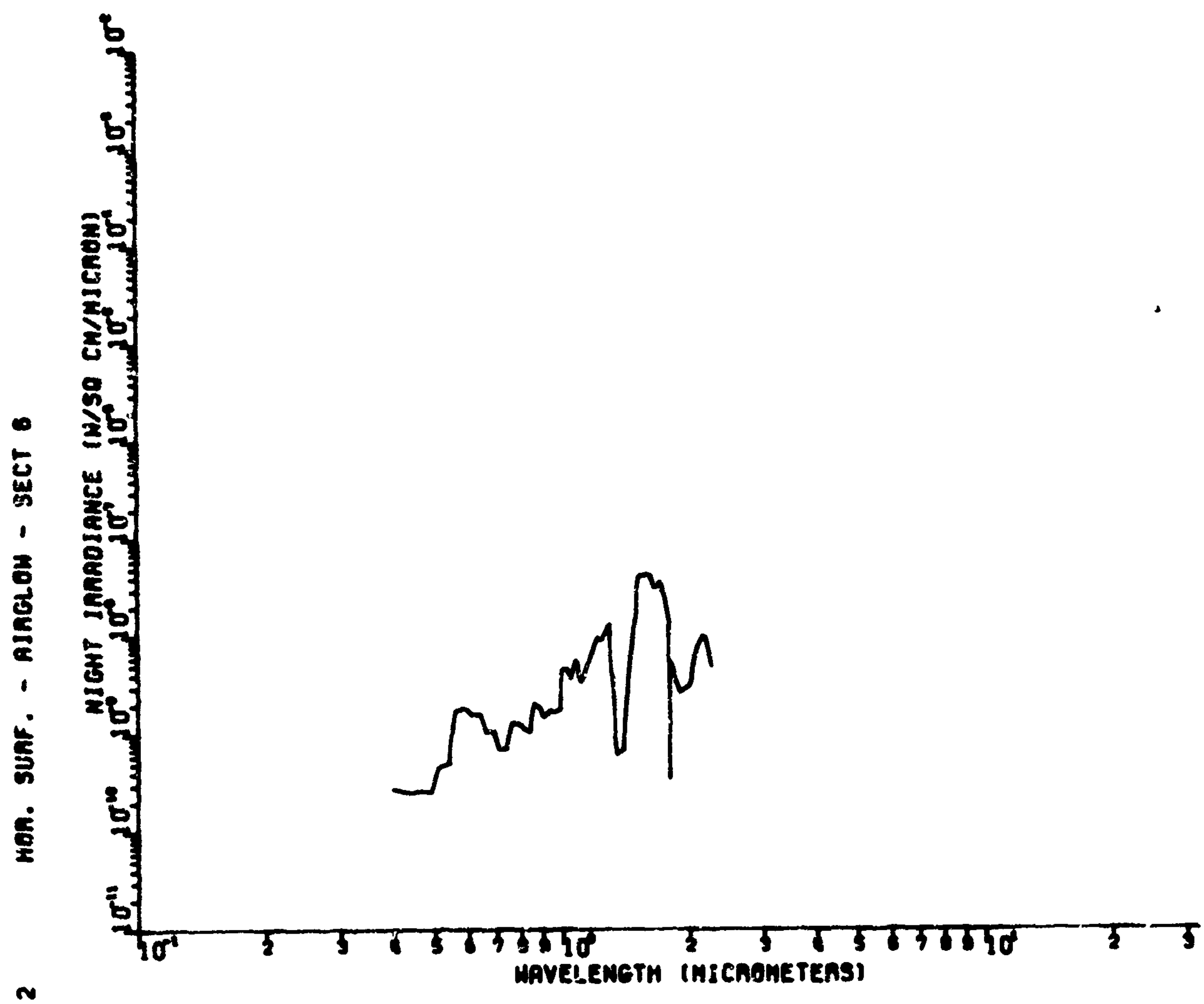


Figure 133. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 6, Zenith Angle of 63.2°

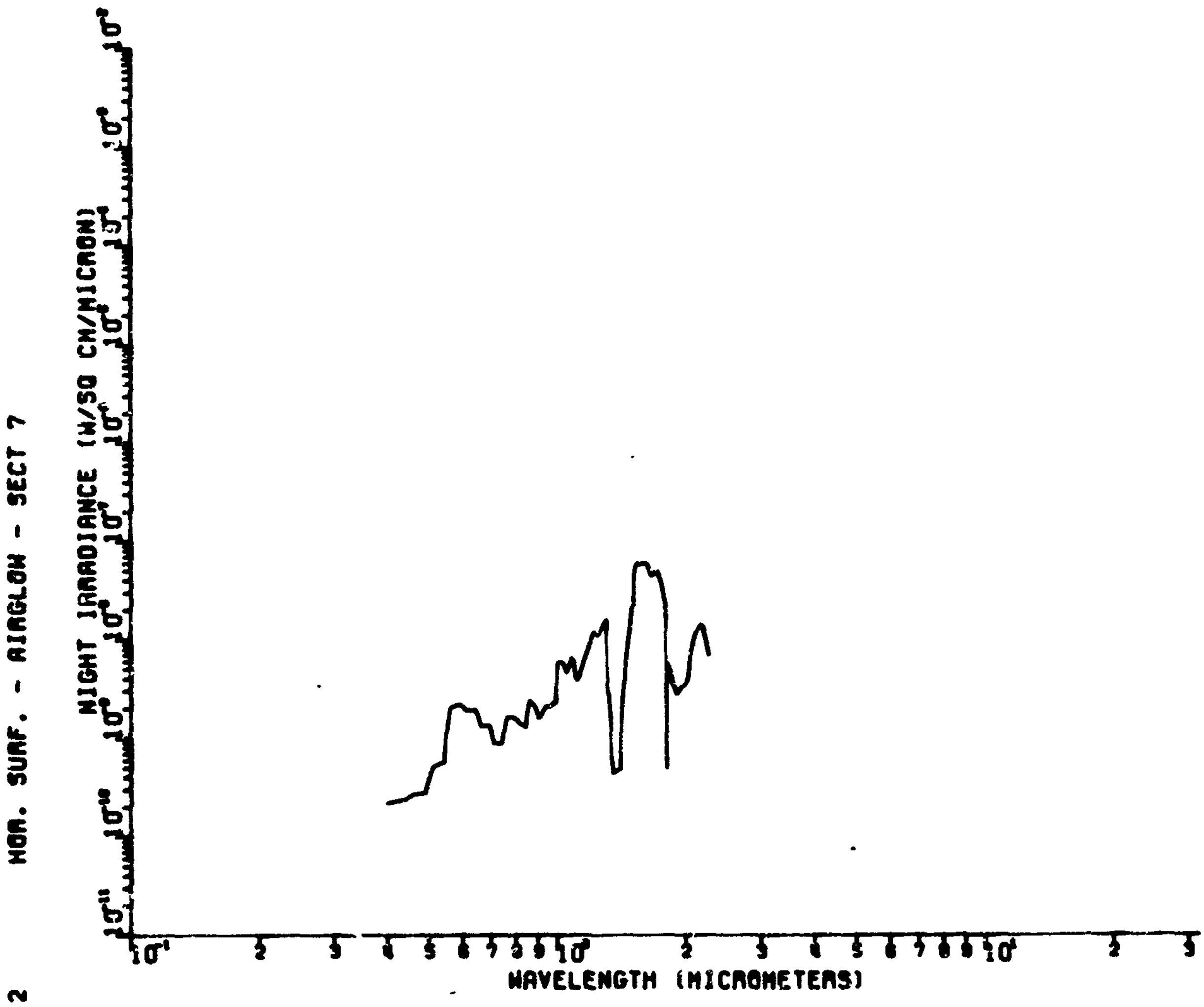


Figure 134. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizonatl Surface, from Sky Segment 7, Zenith Angle of 69.5°

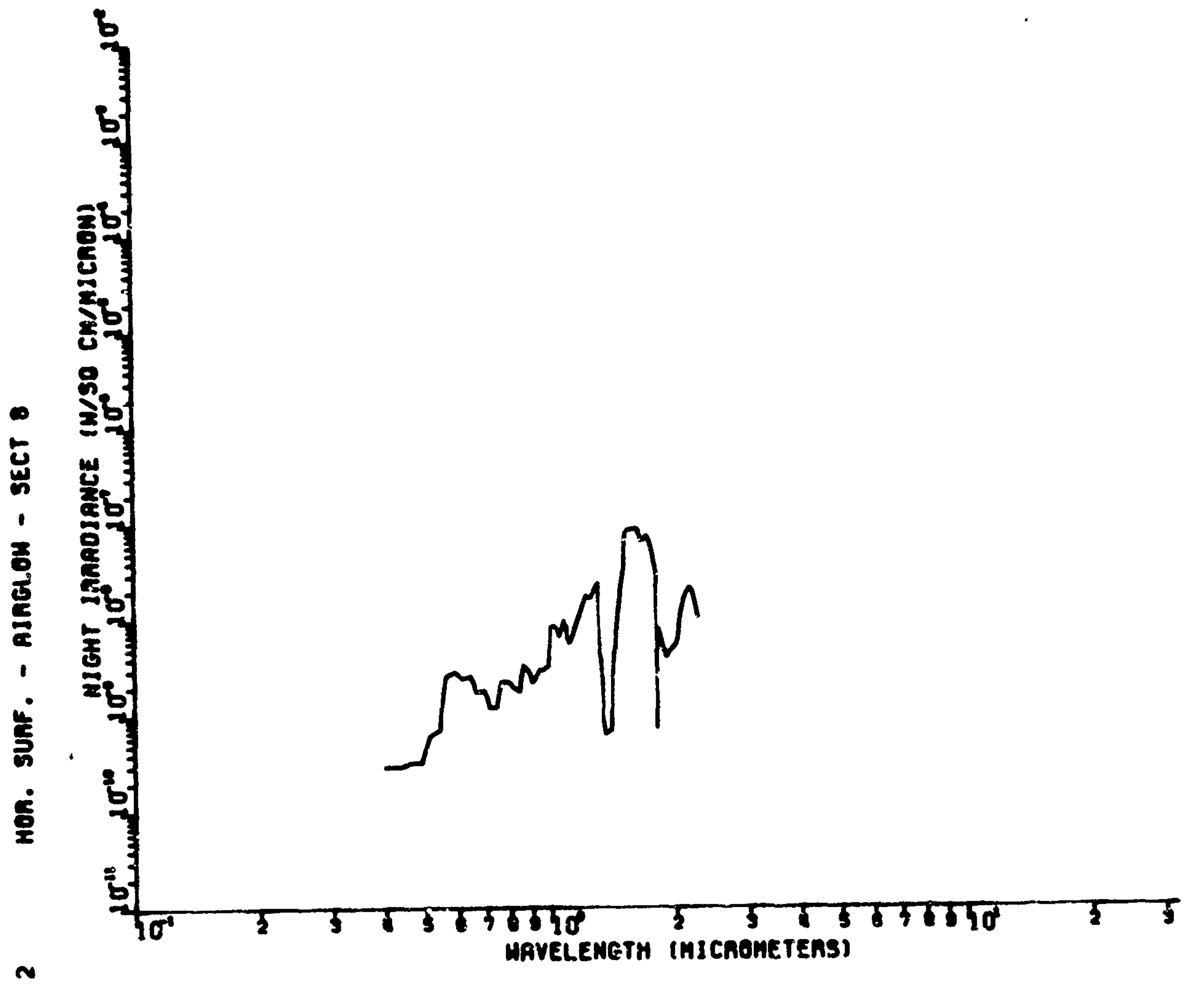


Figure 135. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 8, Zenith Angle of 75.5°

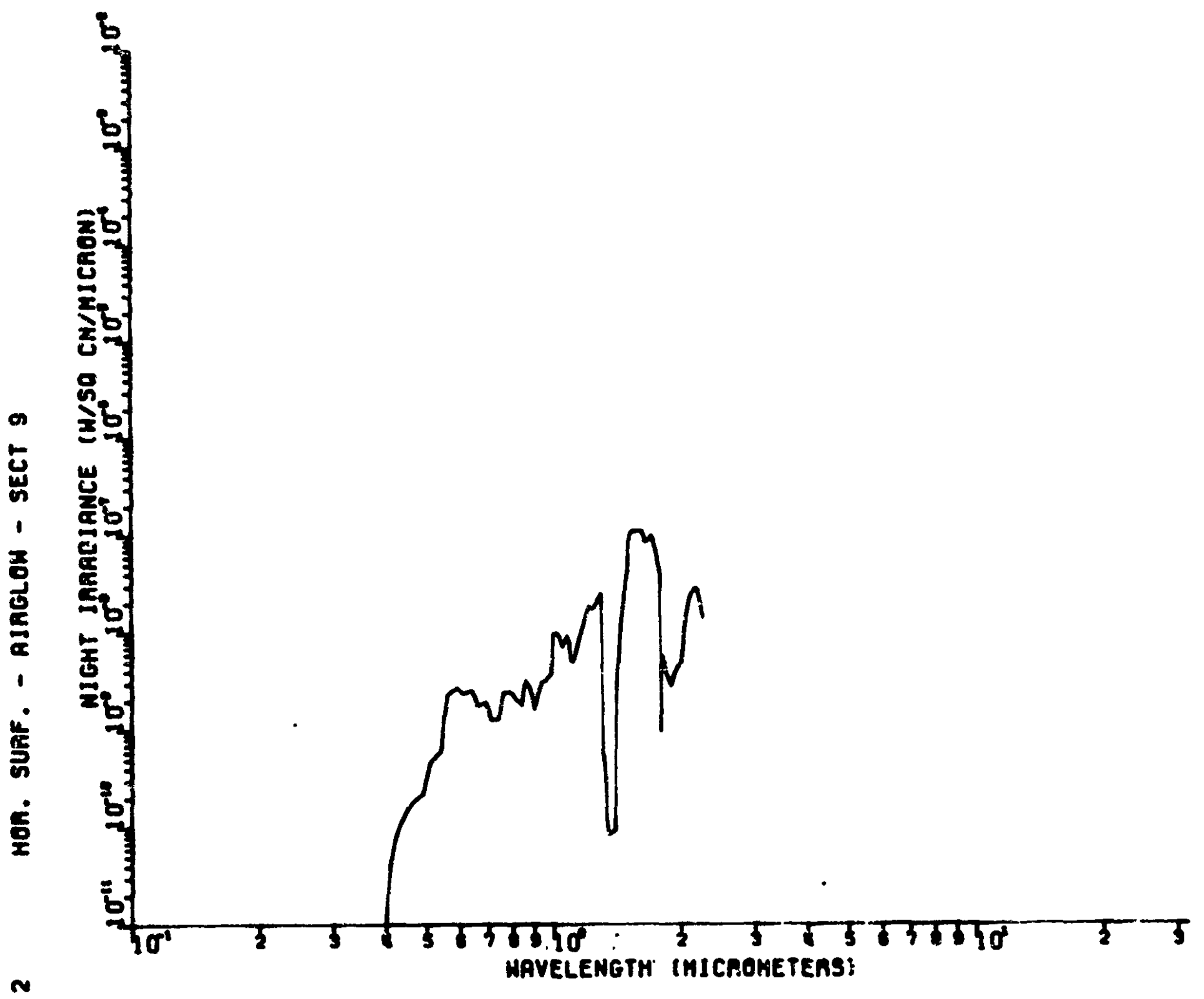


Figure 136. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 9, Zenith Angle of 81.4°

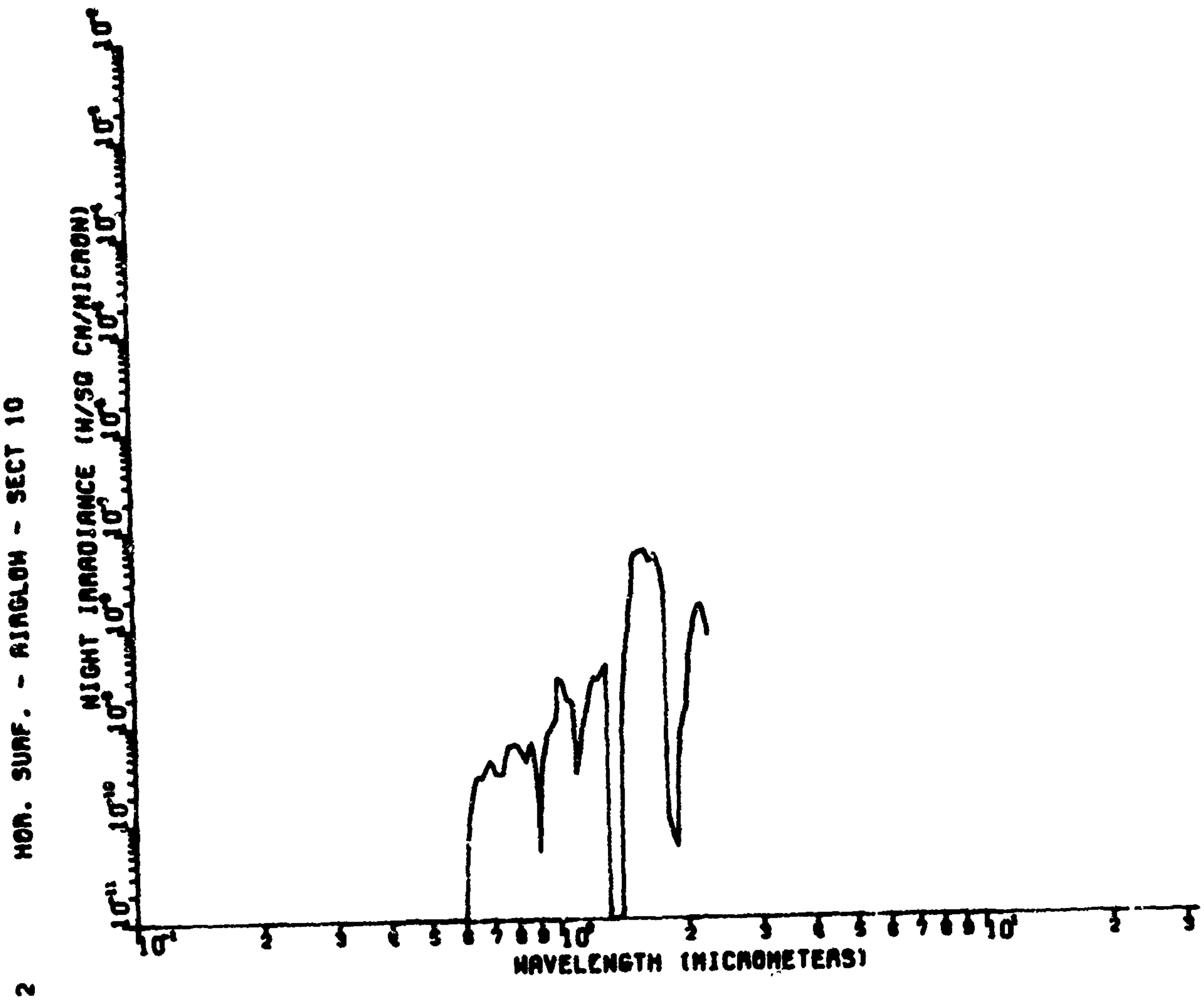


Figure 137. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 10, Zenith Angle of 87.2°

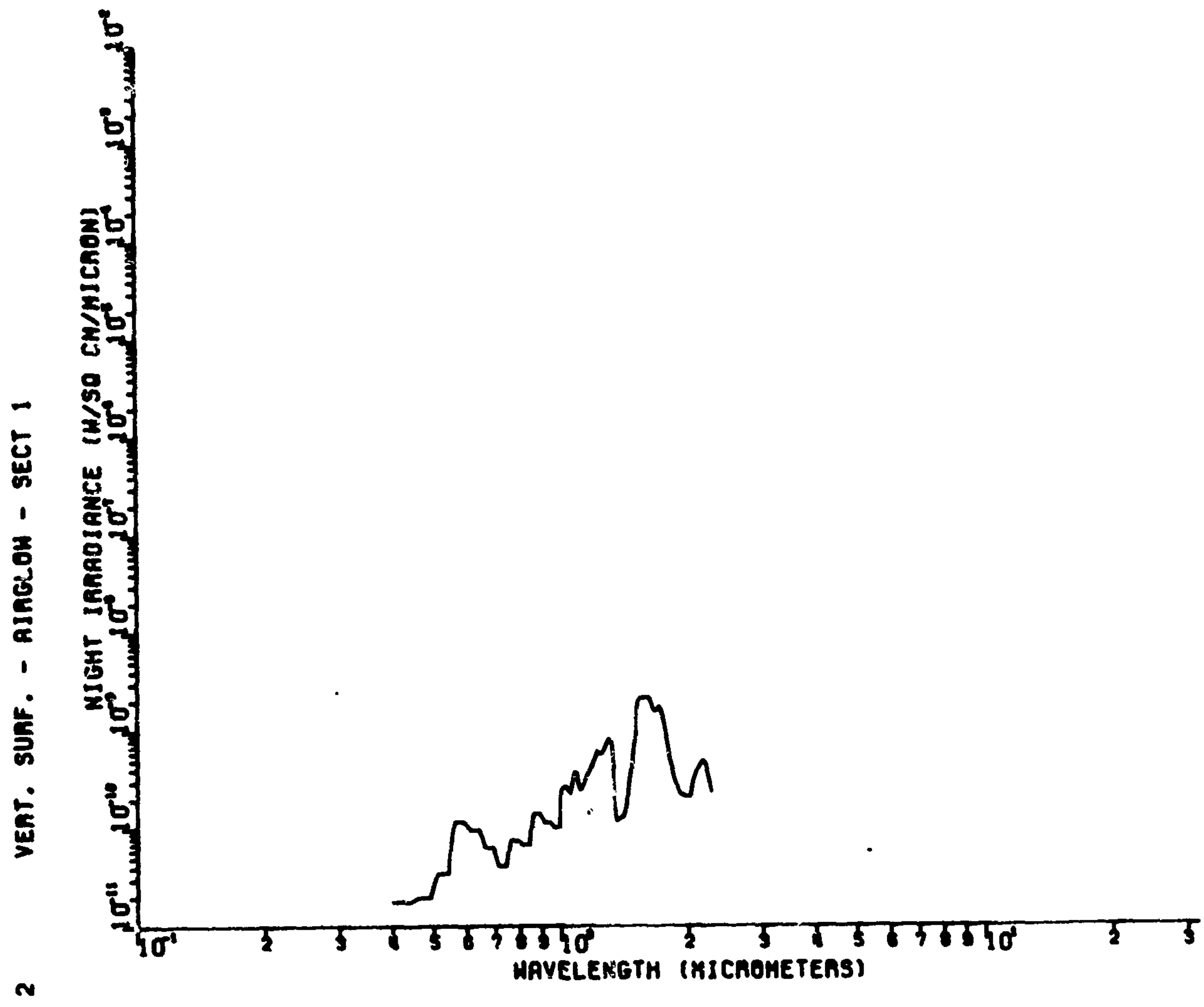


Figure 138. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 1, Zenith Angle of 18.1°

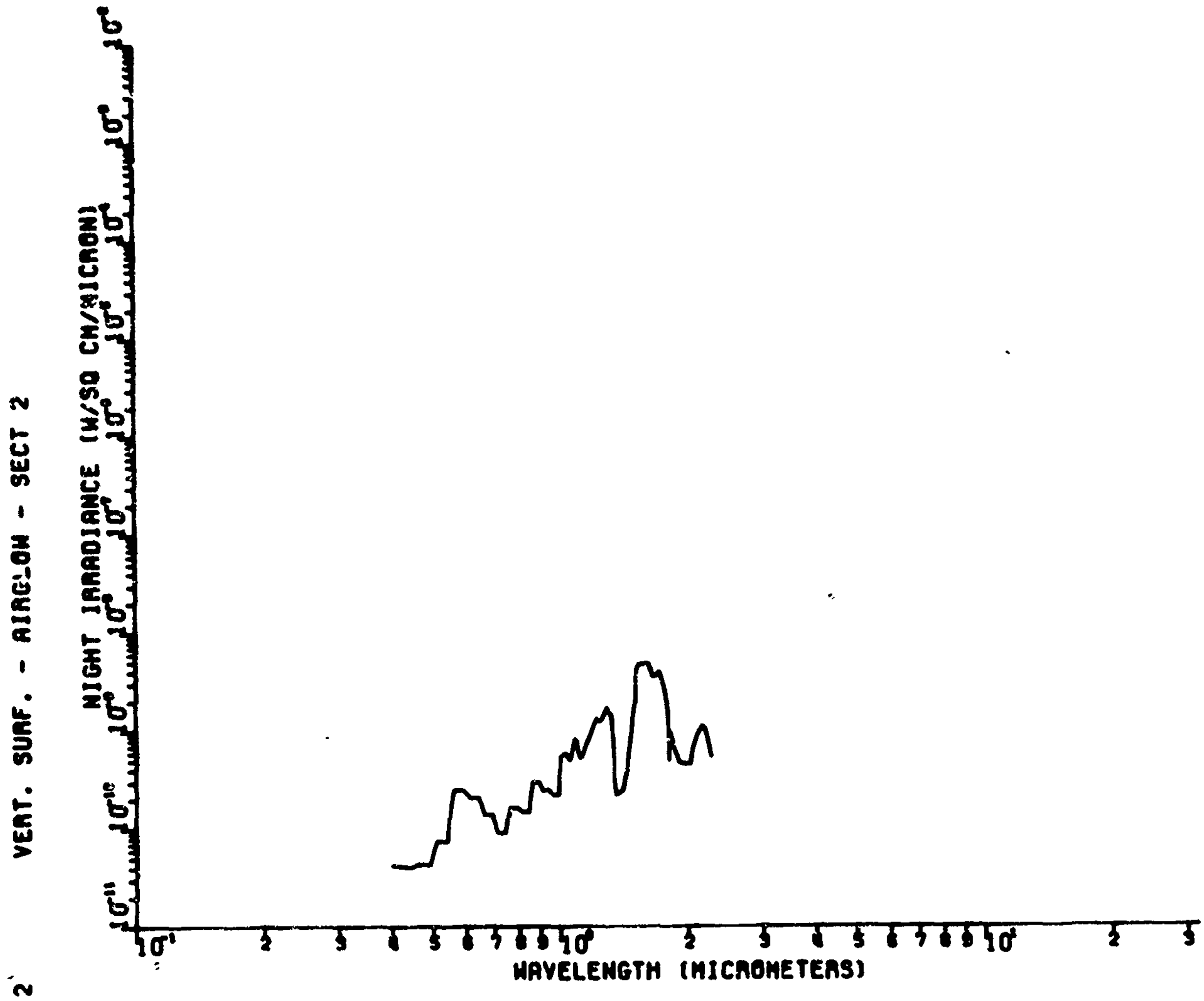


Figure 139. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 2, Zenith Angle of 31.7°

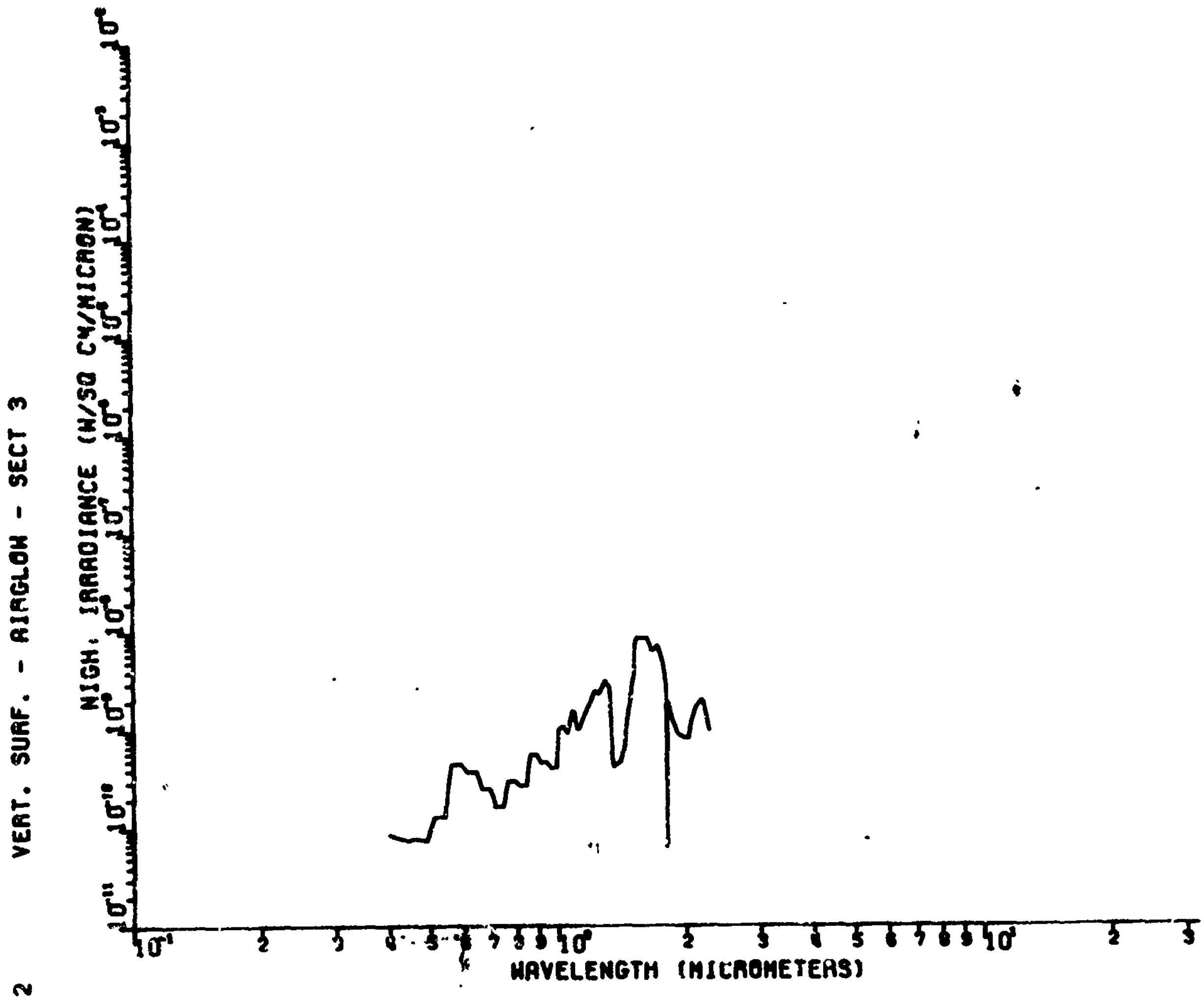


Figure 140. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 3, Zenith Angle of 41.4°

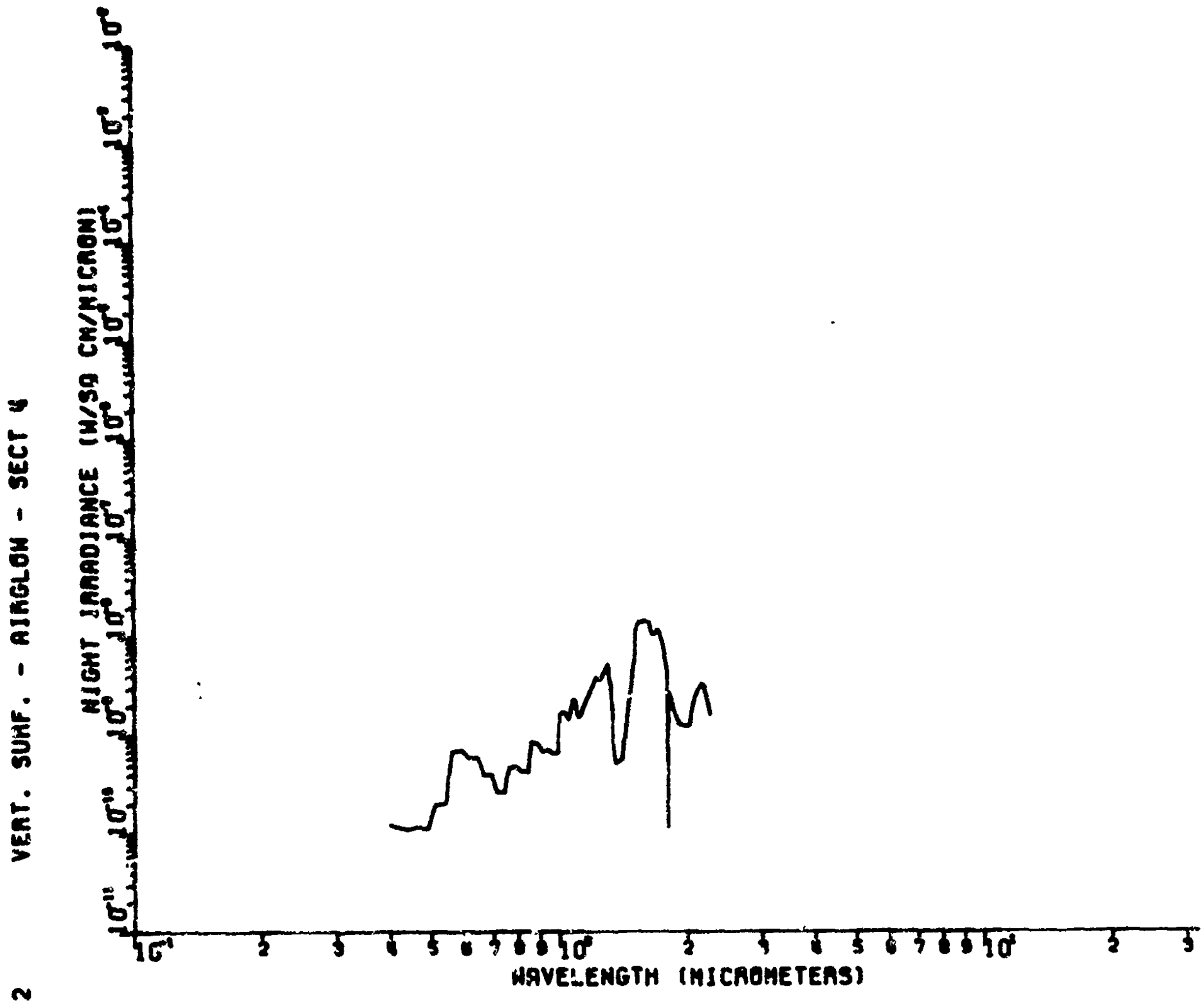


Figure 141. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 4, Zenith Angle of 49.5°

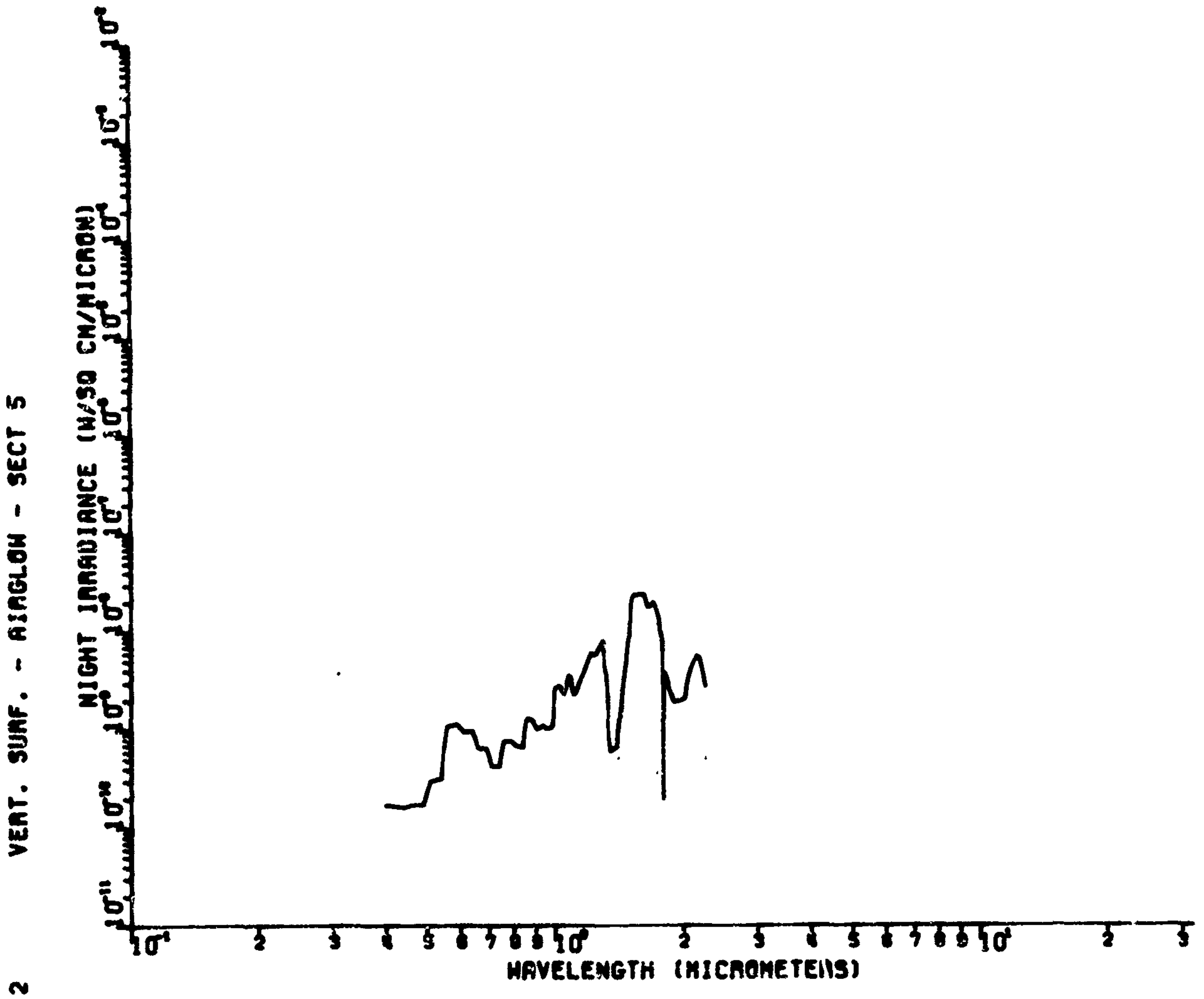


Figure 142. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 5, Zenith Angle of 56.6°

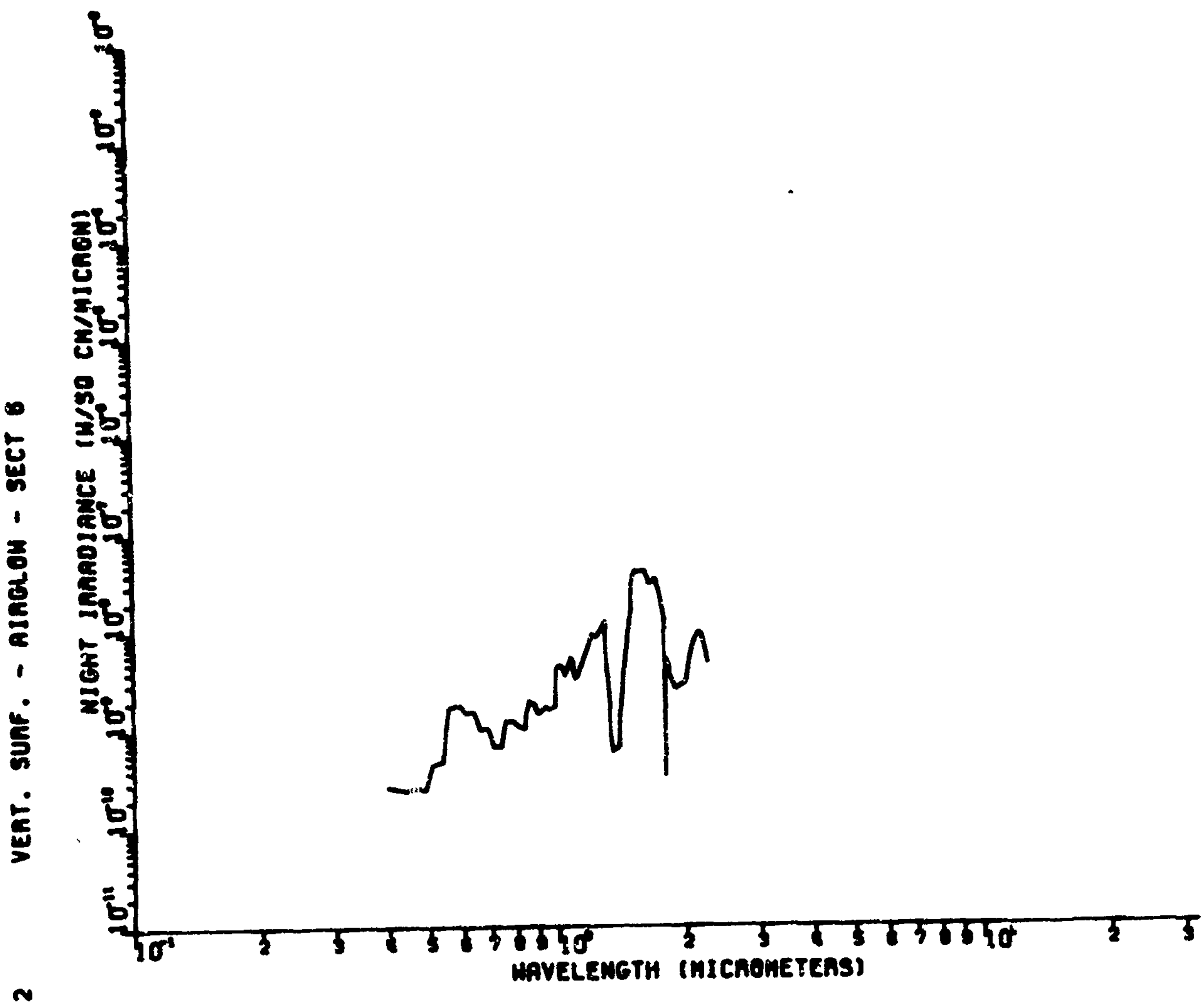


Figure 143. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 6, Zenith Angle of 63.2°

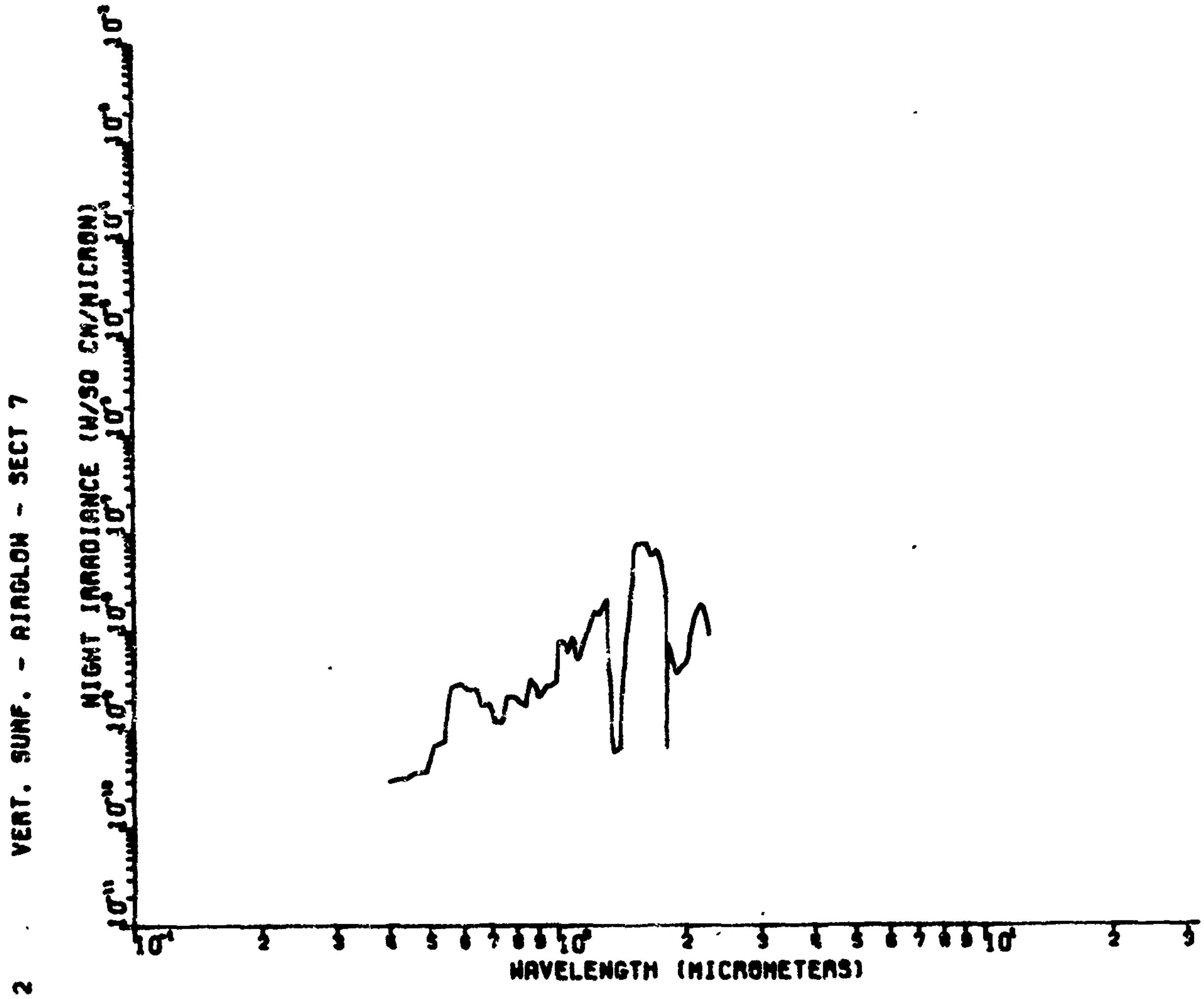


Figure 144. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 7, Zenith Angle of 69.5°

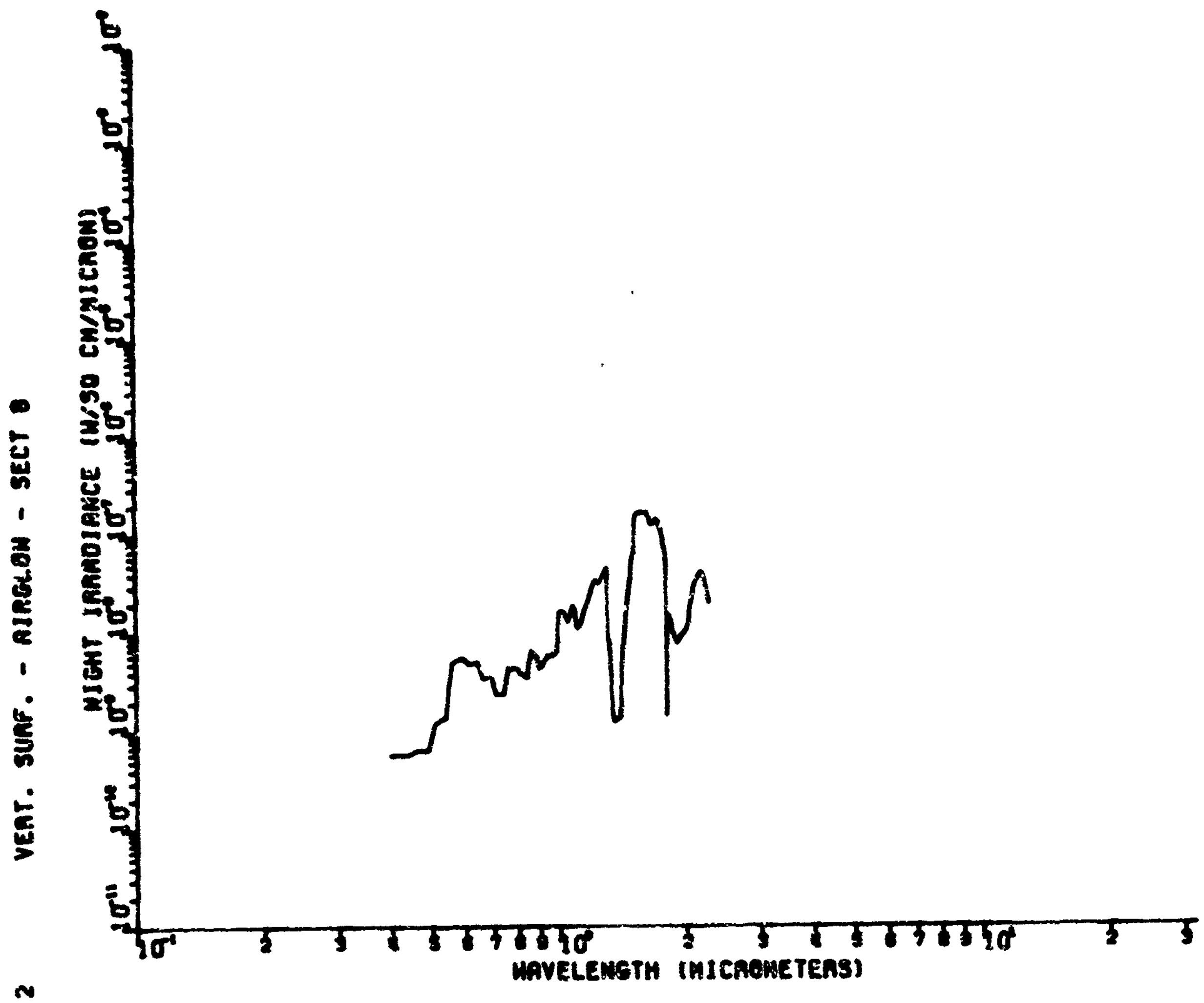


Figure 145. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 8, Zenith Angle of 75.5°

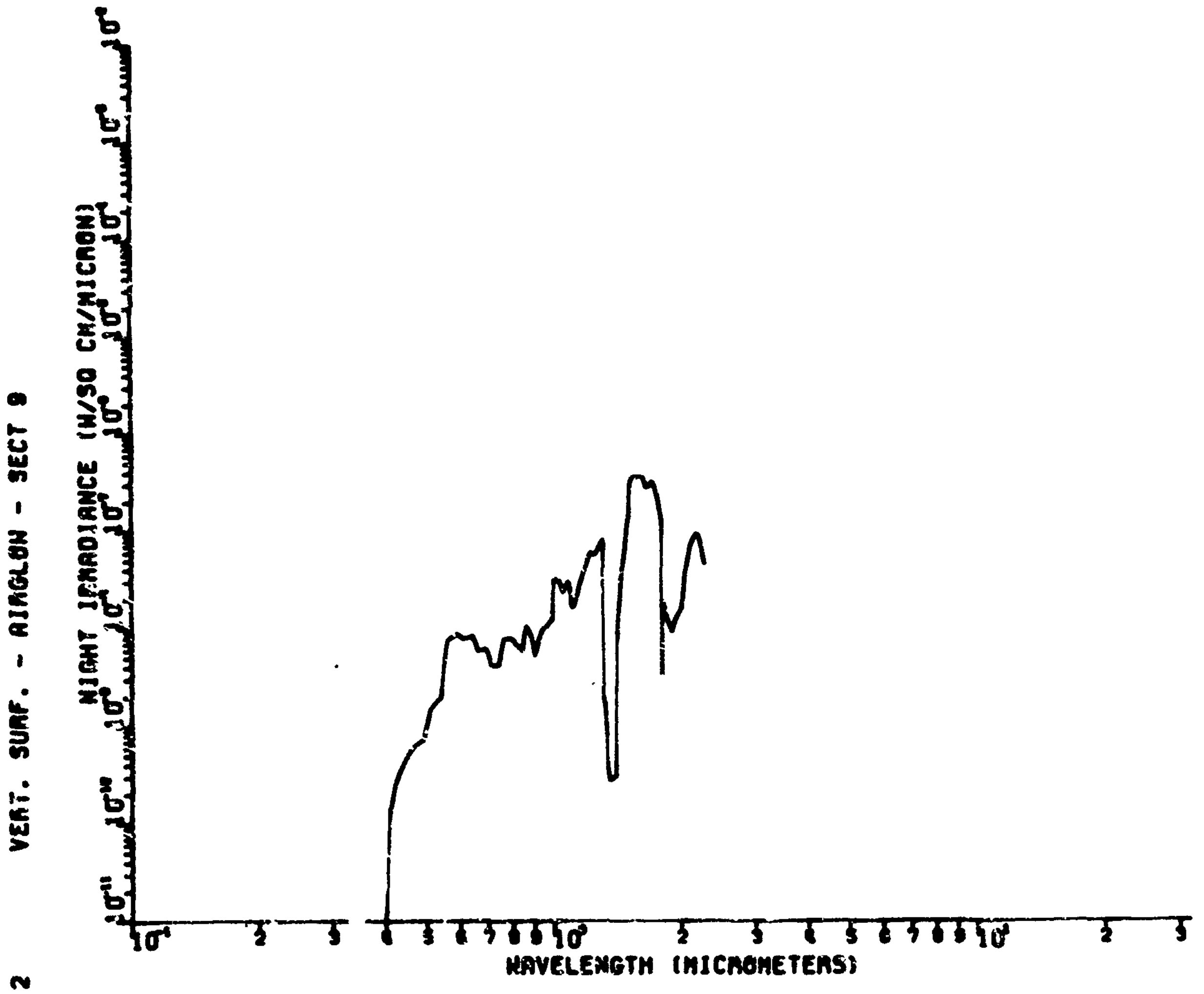


Figure 146. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 9, Zenith Angle of 81.4°

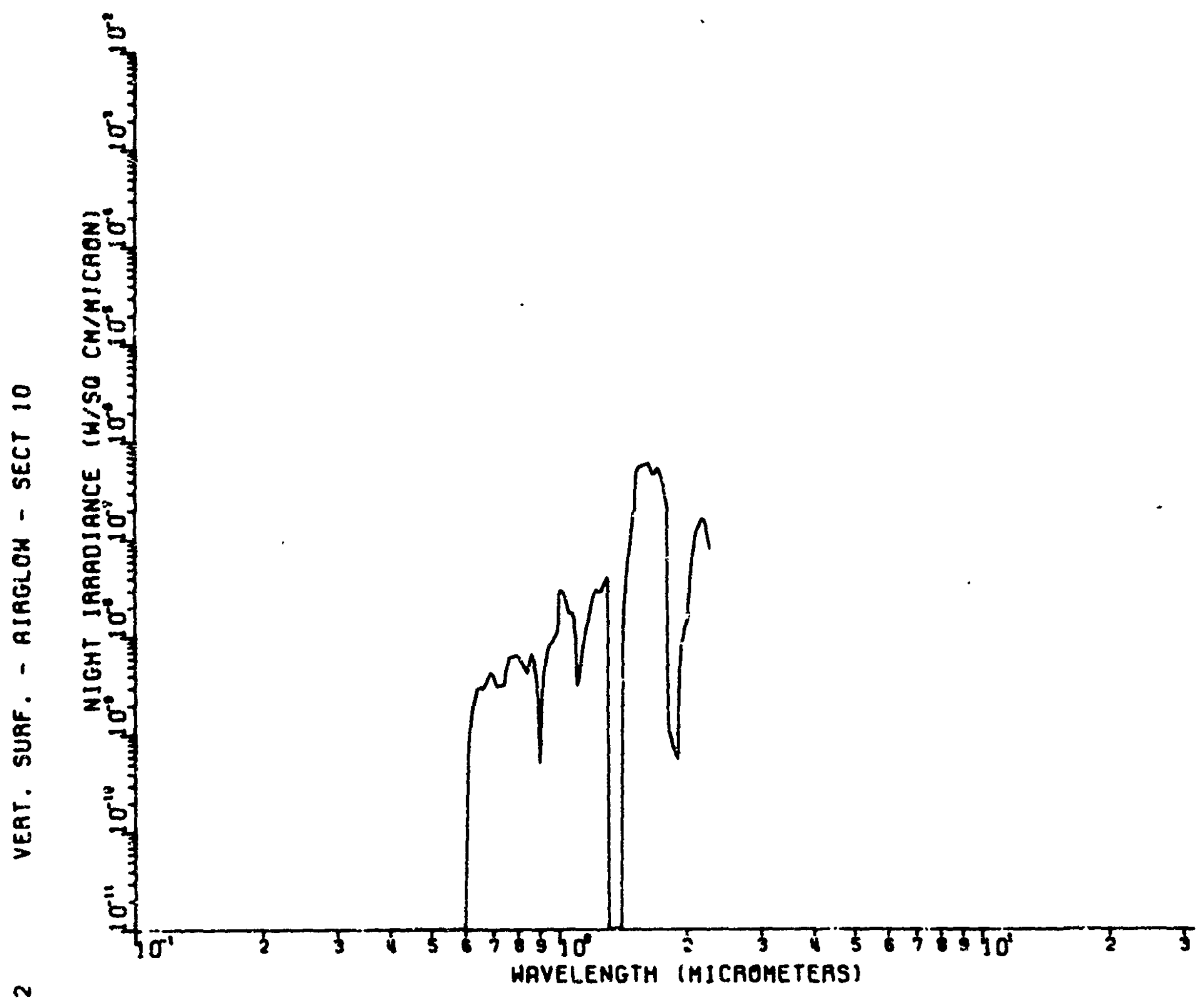


Figure 147. Spectral Nightglow Irradiance for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 10, Zenith Angle of 87.2°

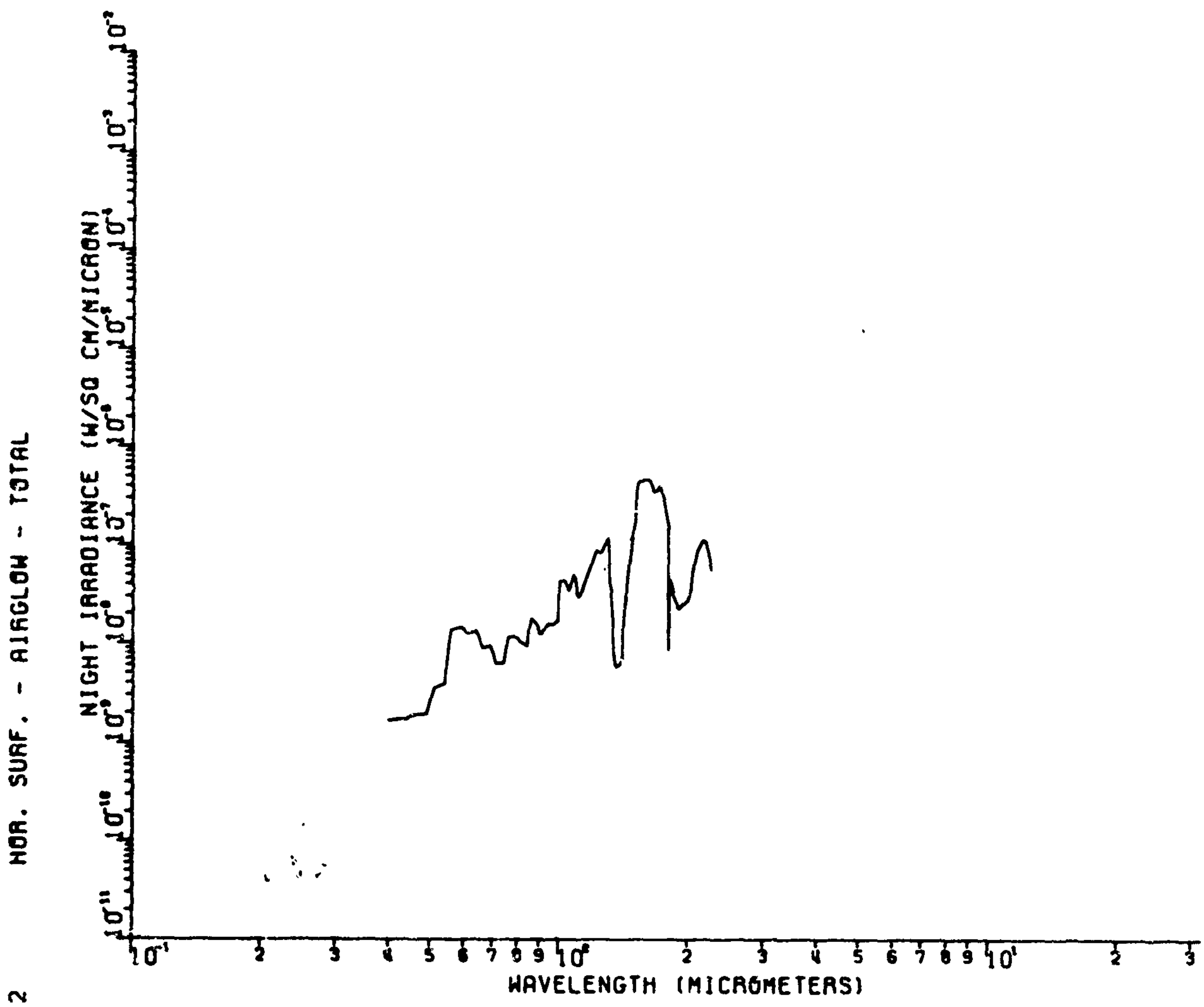


Figure 148. Total Spectral Nightglow Irradiance Illuminating a Horizontal Surface

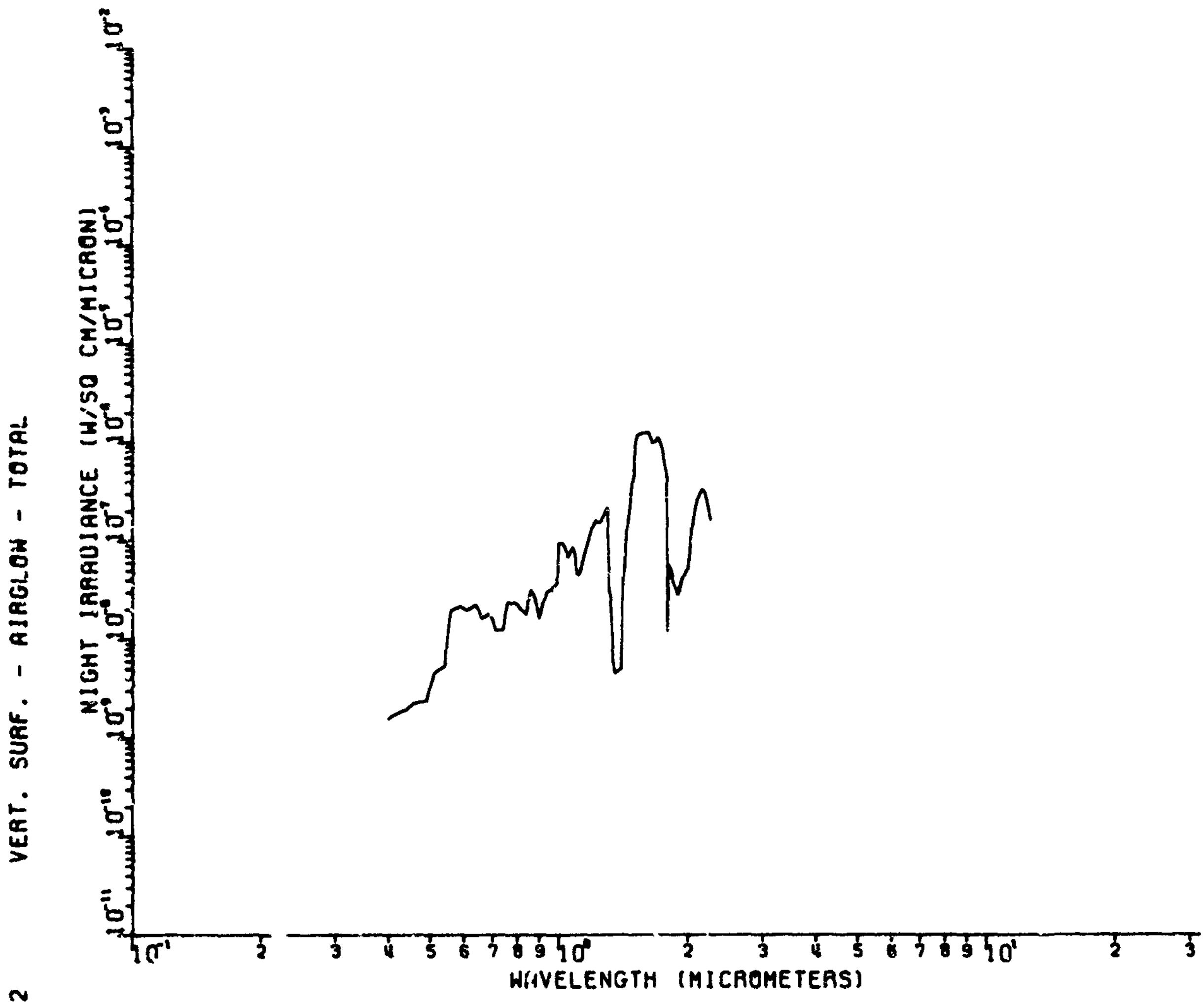


Figure 149. Total Spectral Nightglow Irradiance Illuminating a Vertical Surface

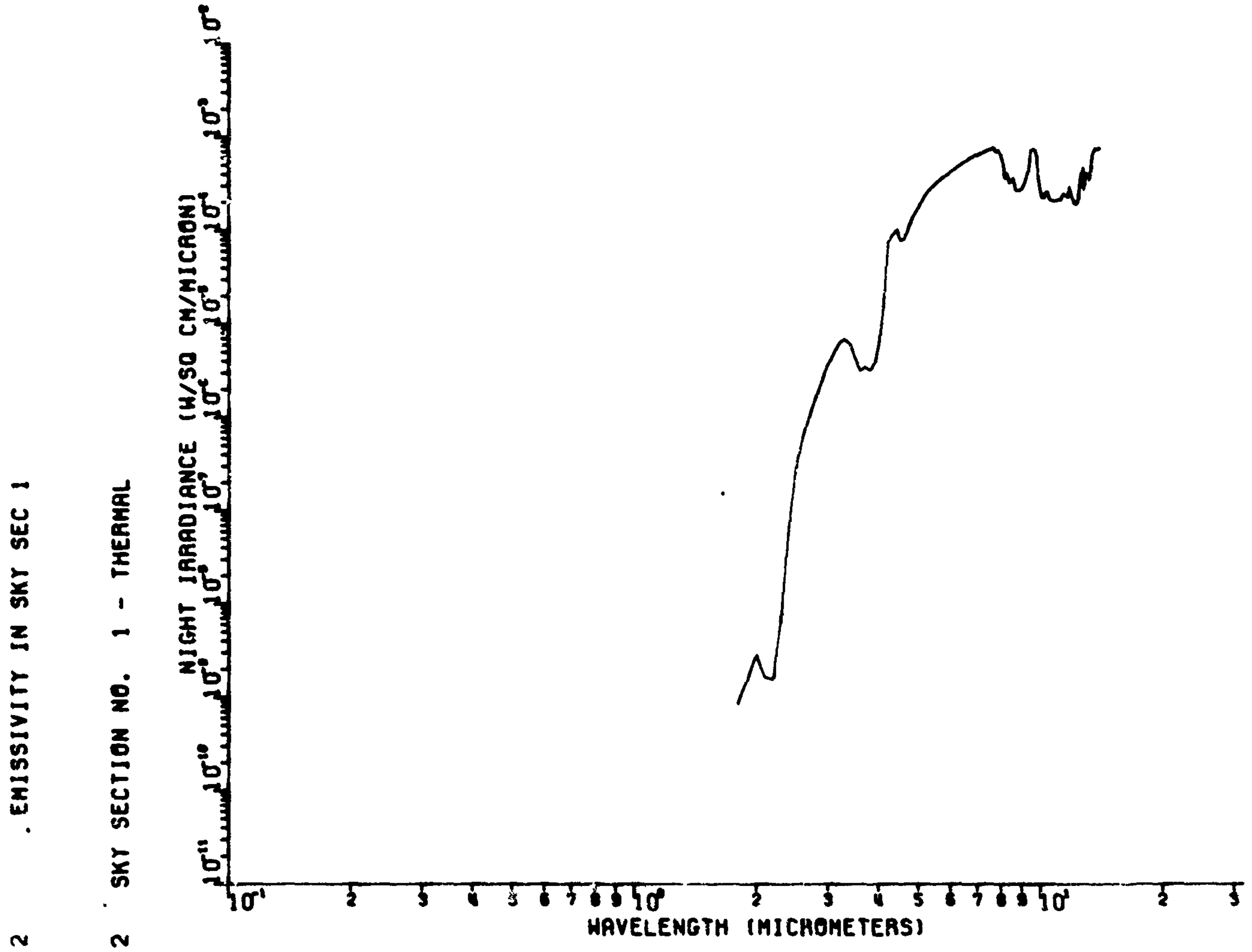


Figure 150. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 1, Zenith Angle of 18.1°

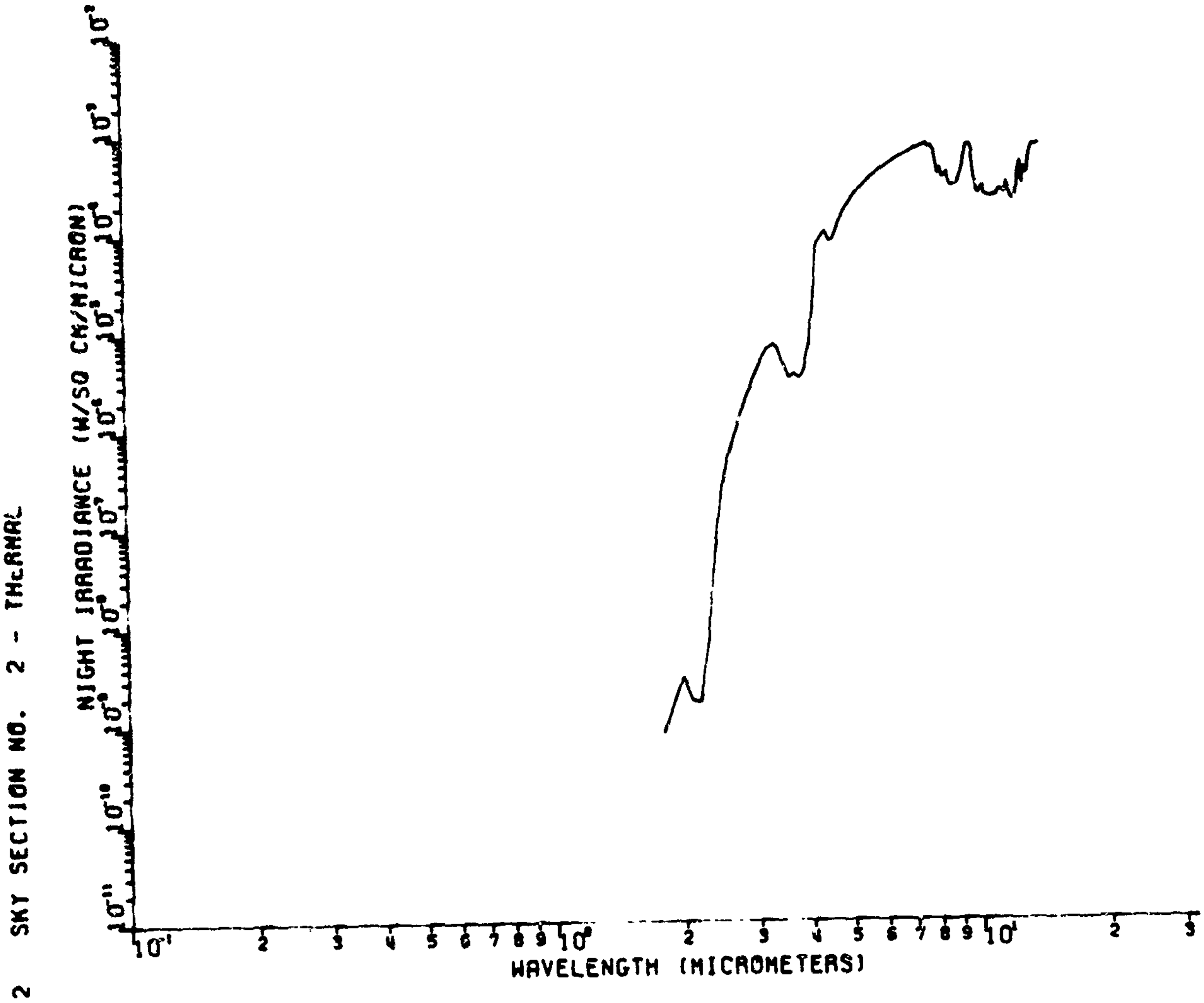


Figure 151. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 2, Zenith Angle of 31.7°

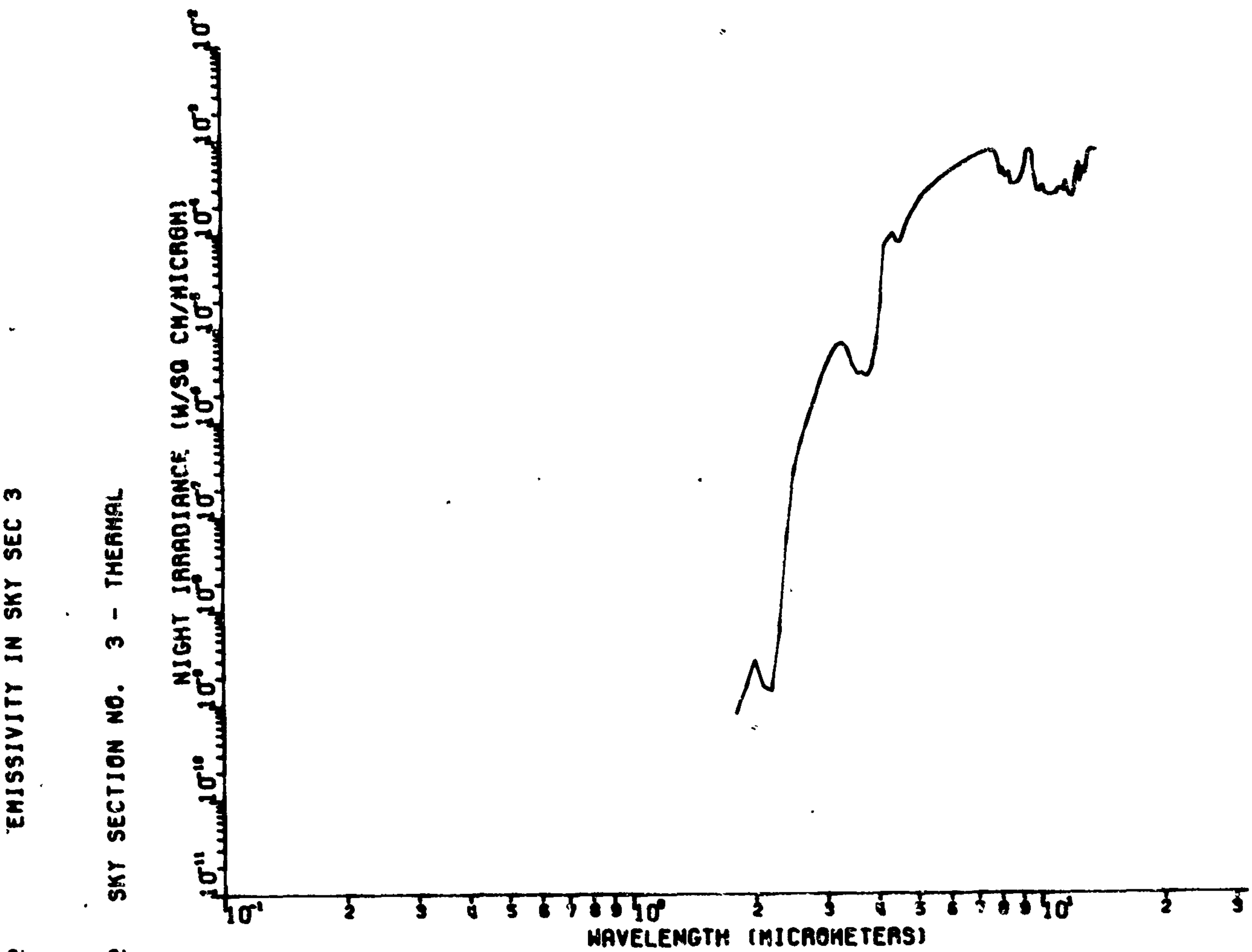


Figure 152. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 3, Zenith Angle of 41.4°

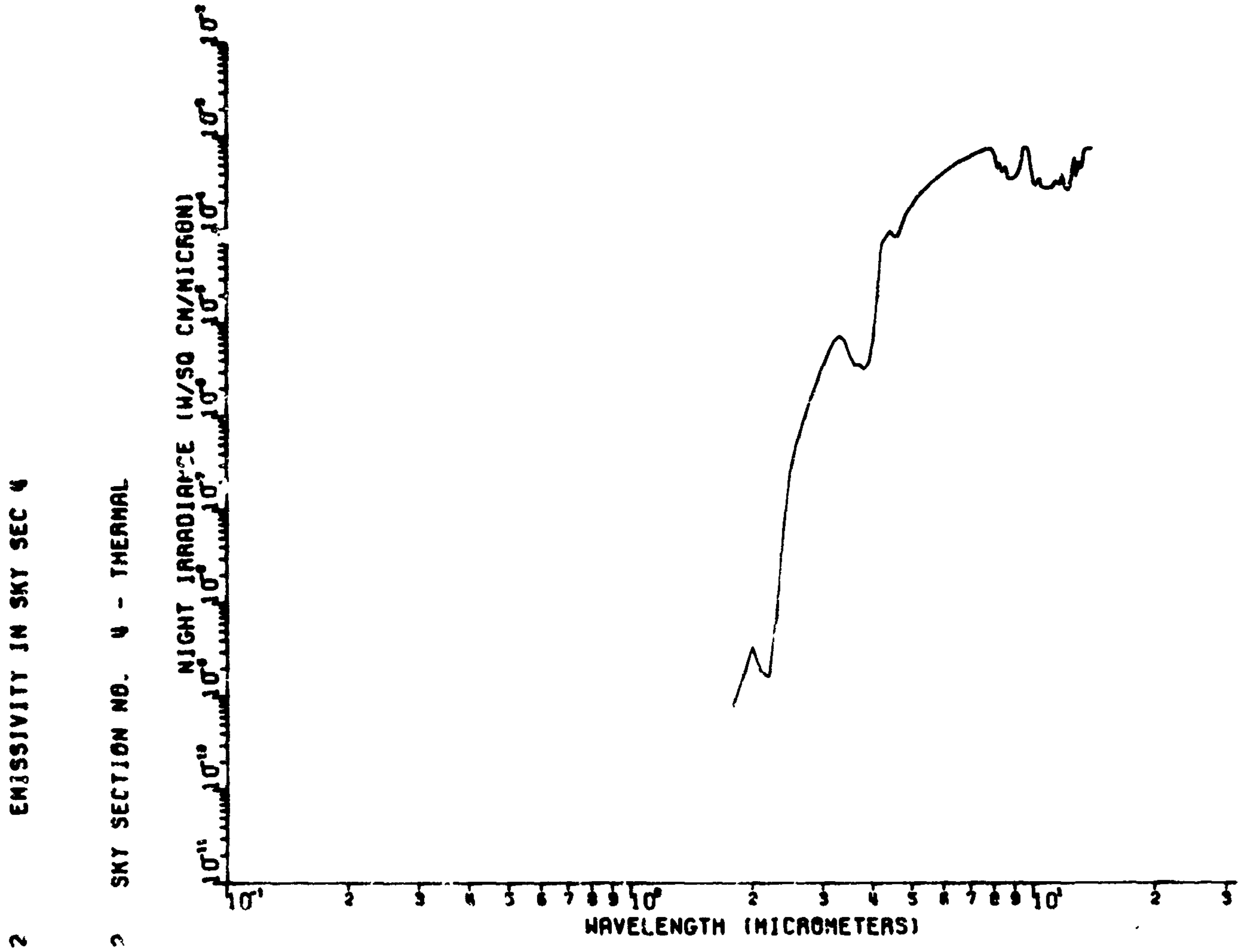


Figure 153. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 4, Zenith Angle of 49.5°

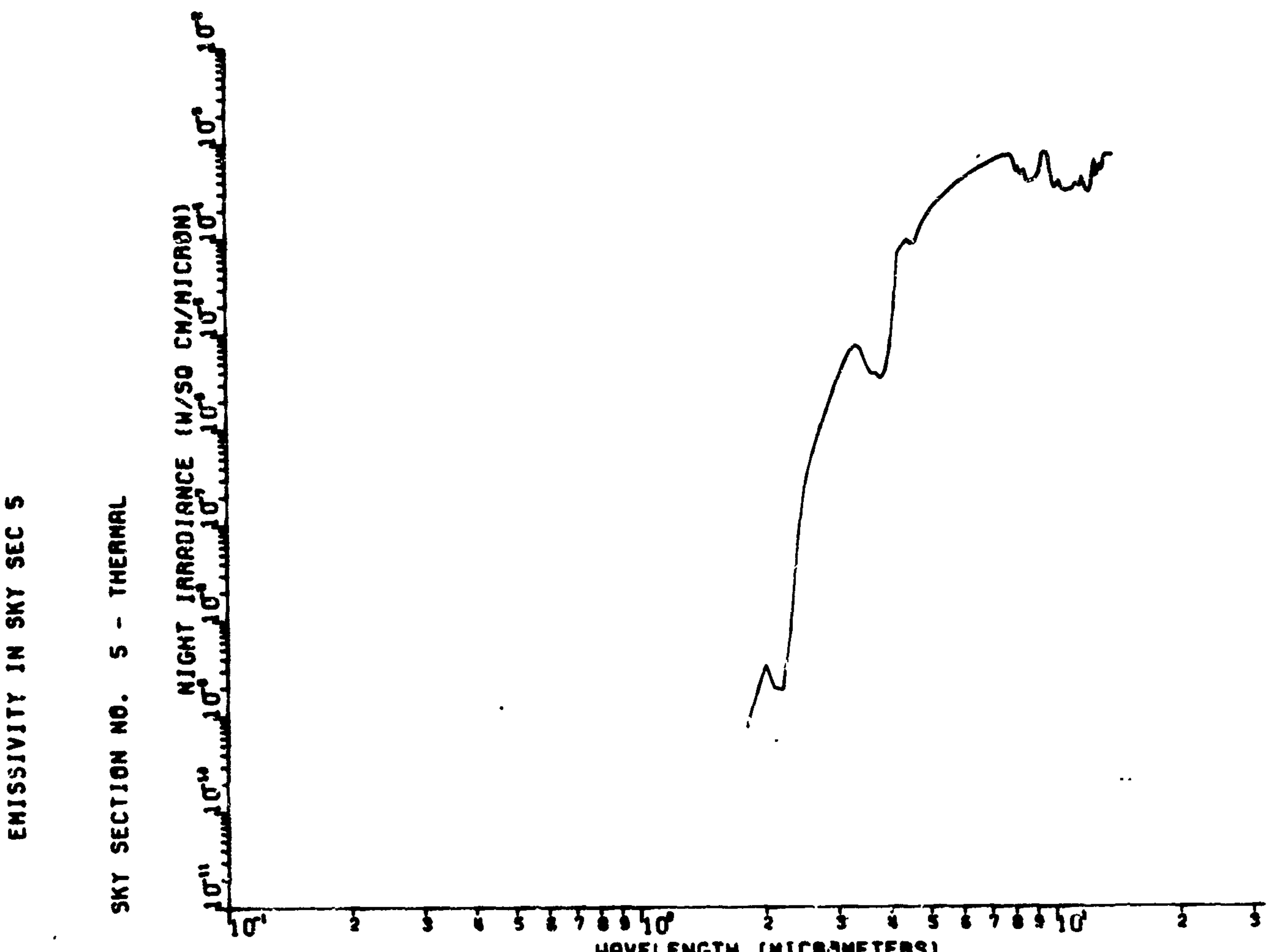


Figure 154. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 5, Zenith Angle of 56.6°

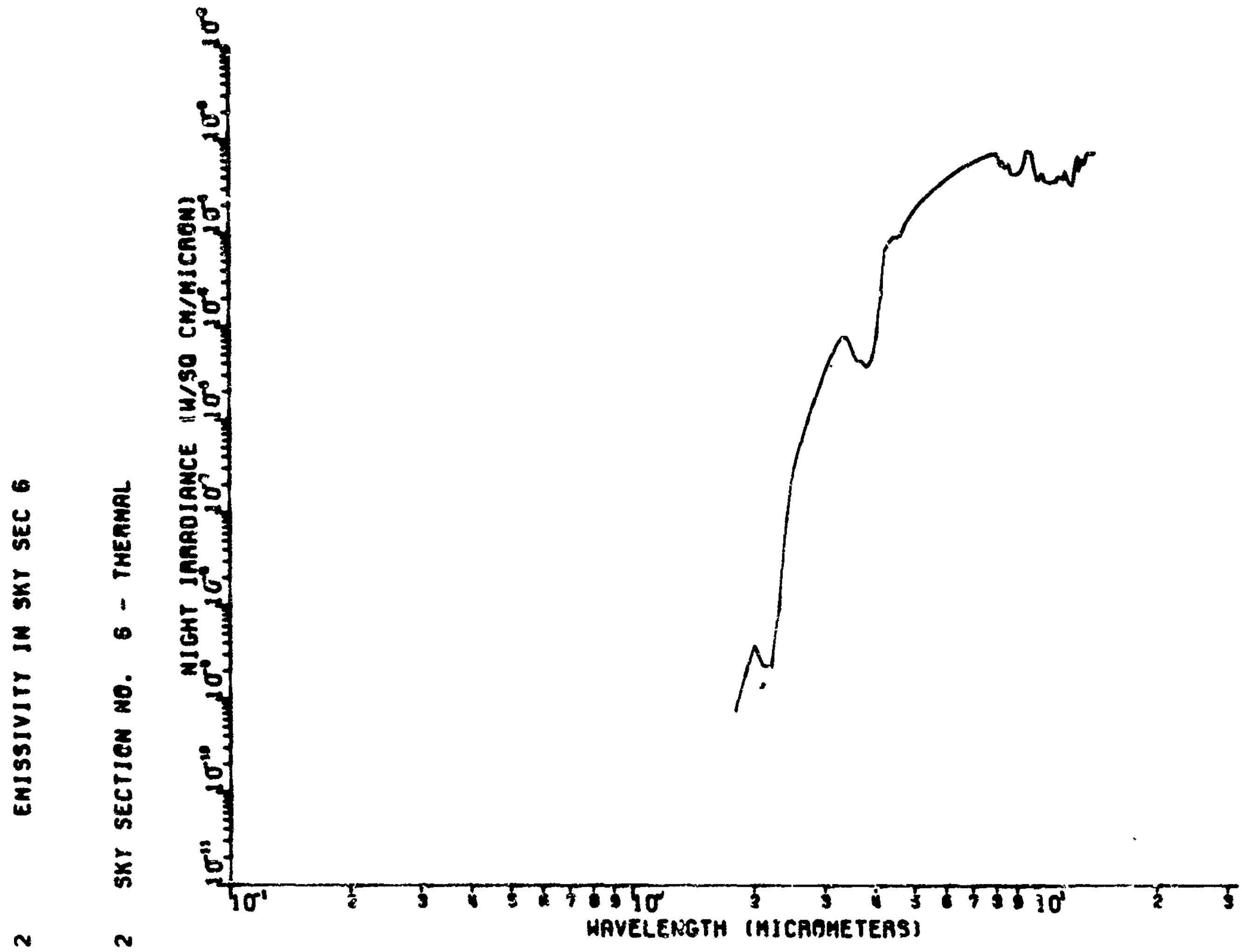


Figure 155. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 6, Zenith Angle of 63.2°

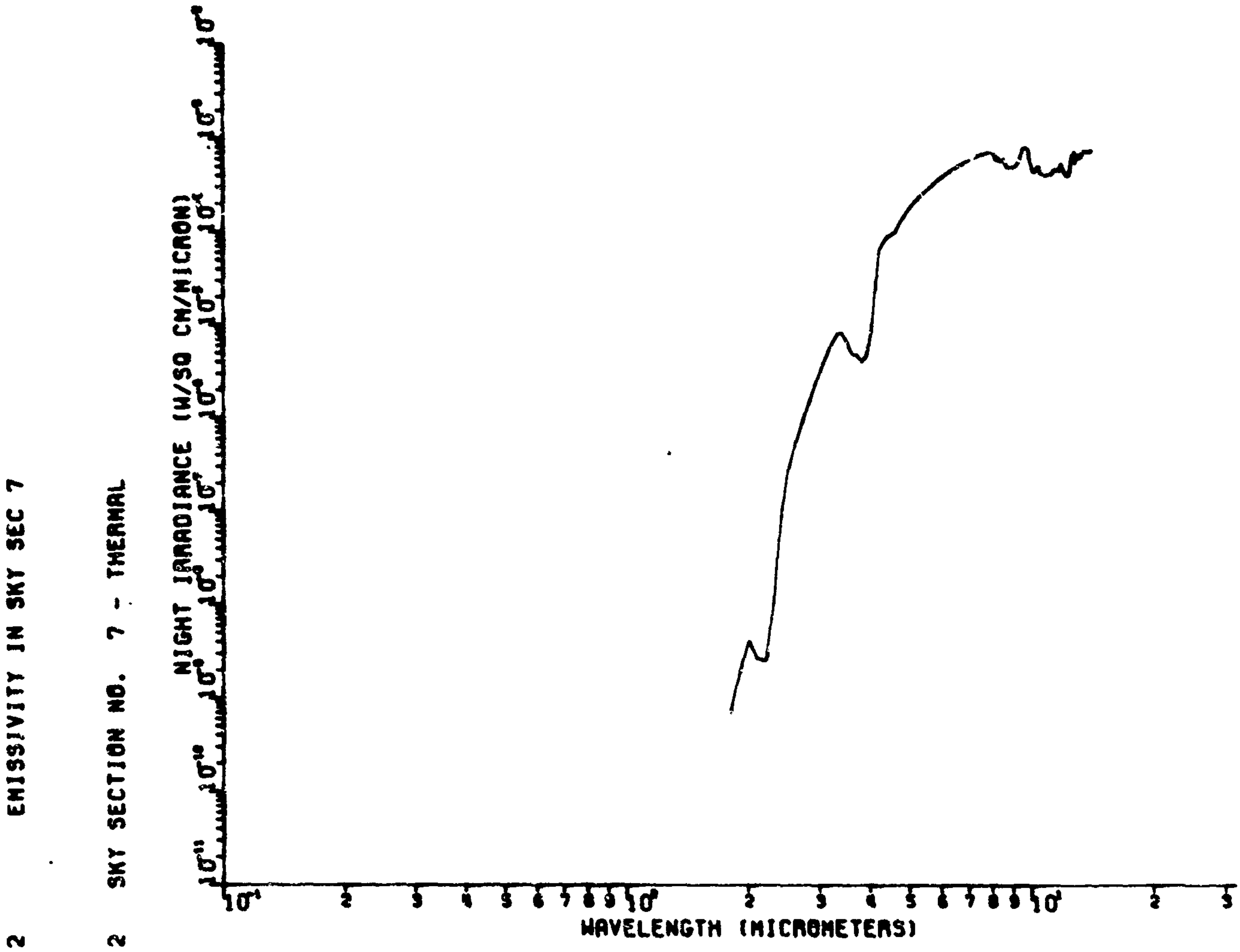


Figure 156. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 7, Zenith Angle of 69.5°

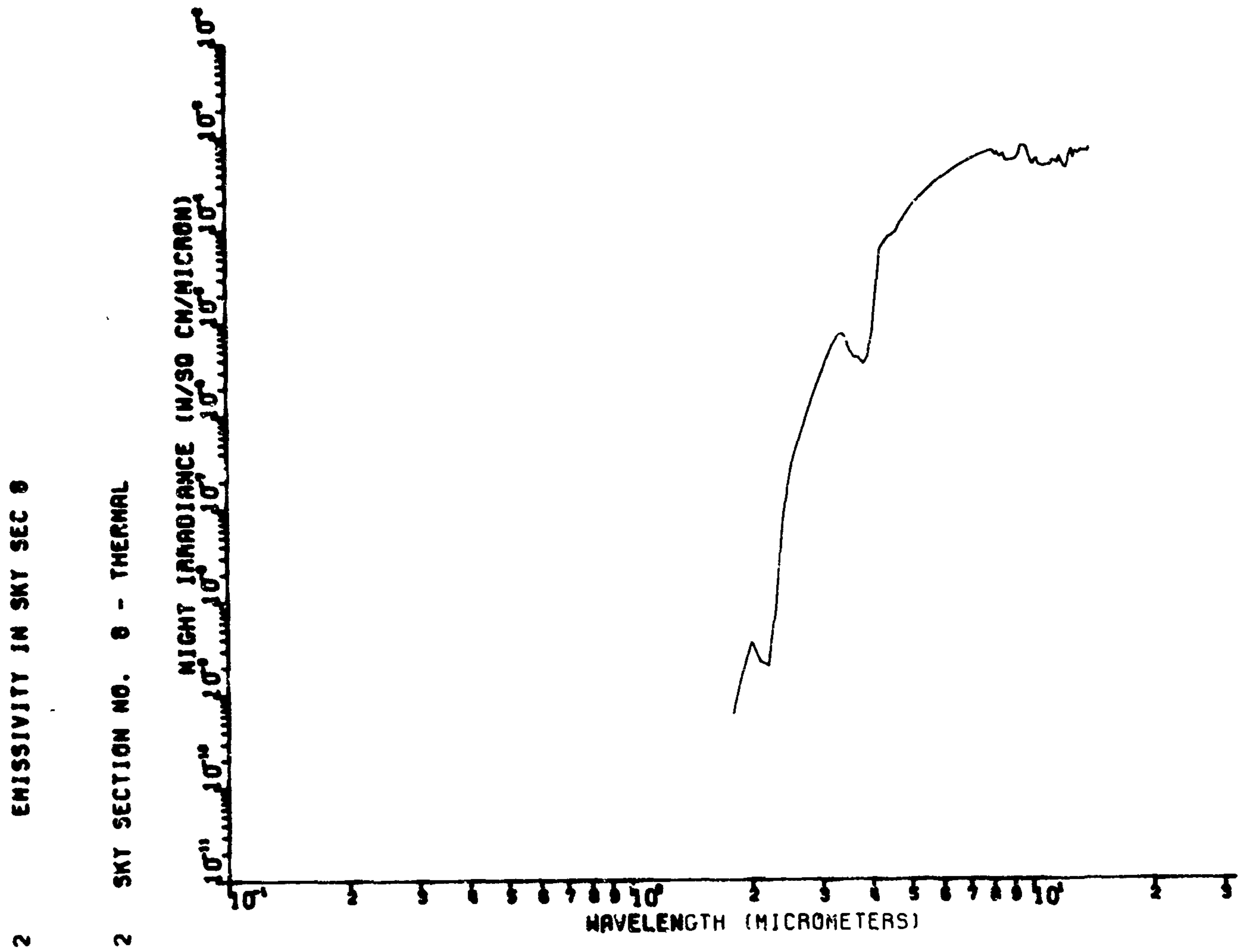


Figure 157. Tropospheric Thermal Energy for 0. 1 of the Sky at the Surface, Sky Segment 8, Zenith Angle of 75. 5°

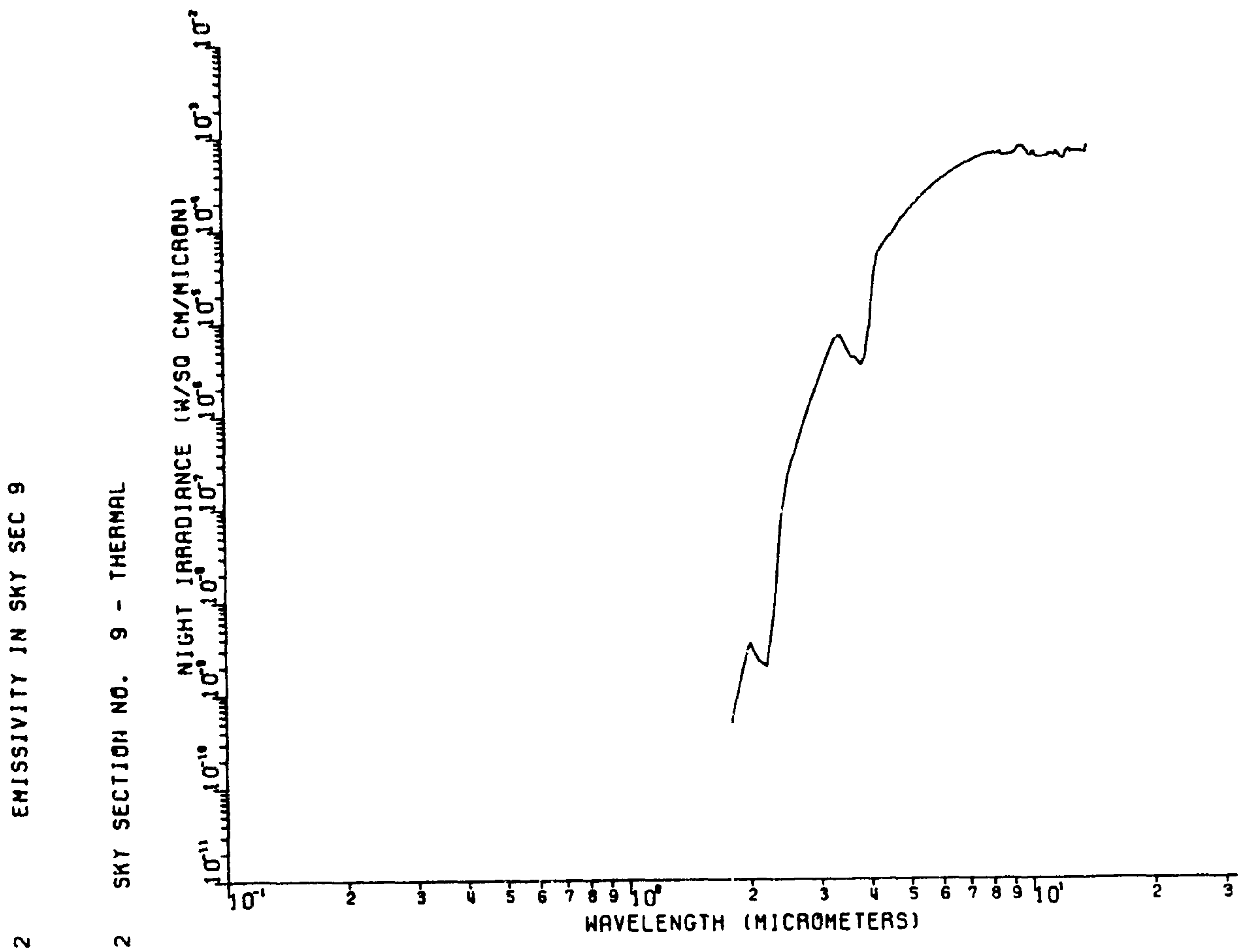


Figure 158. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 9, Zenith Angle of 81.4°

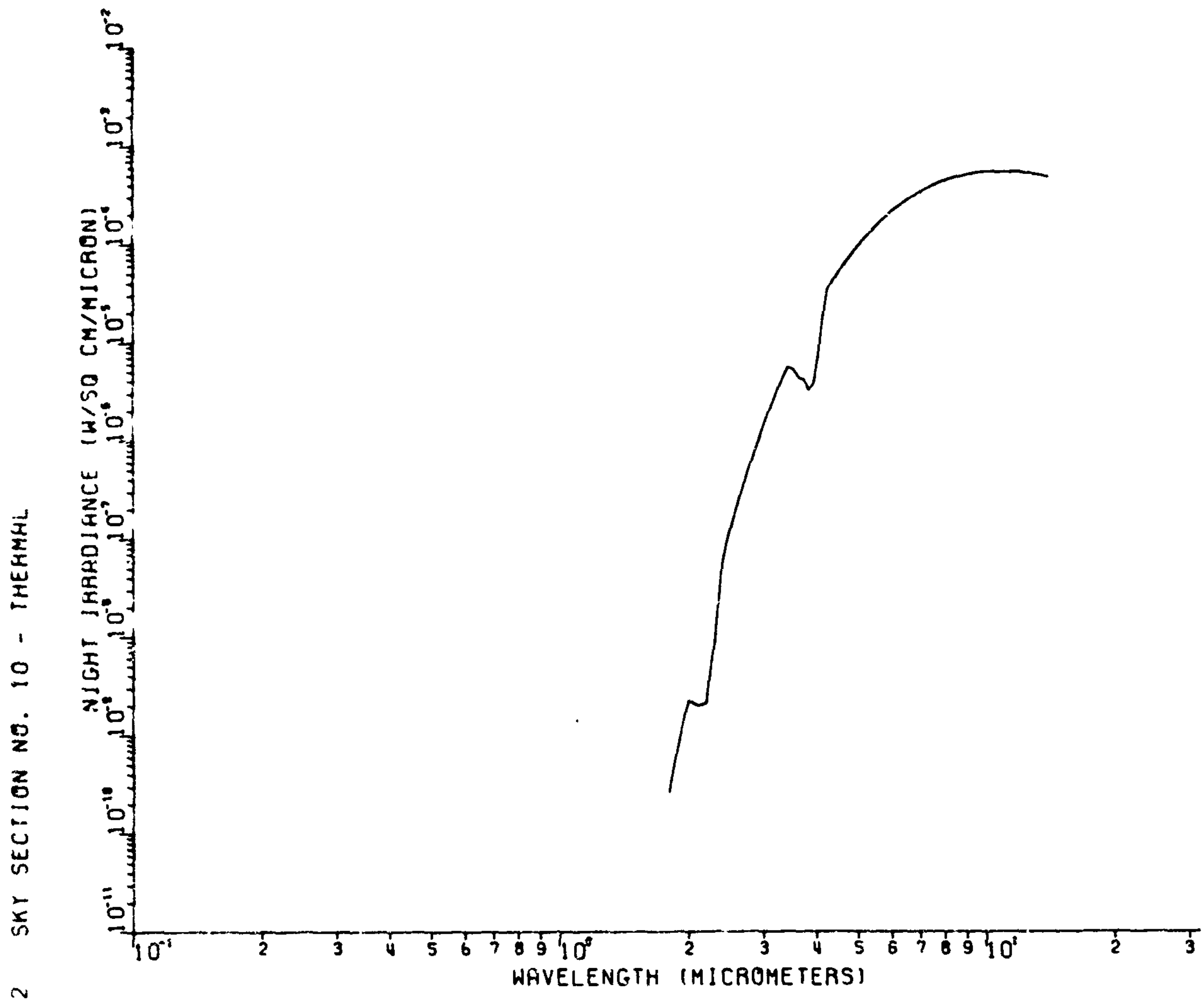


Figure 159. Tropospheric Thermal Energy for 0.1 of the Sky at the Surface, Sky Segment 10, Zenith Angle of 87.2°

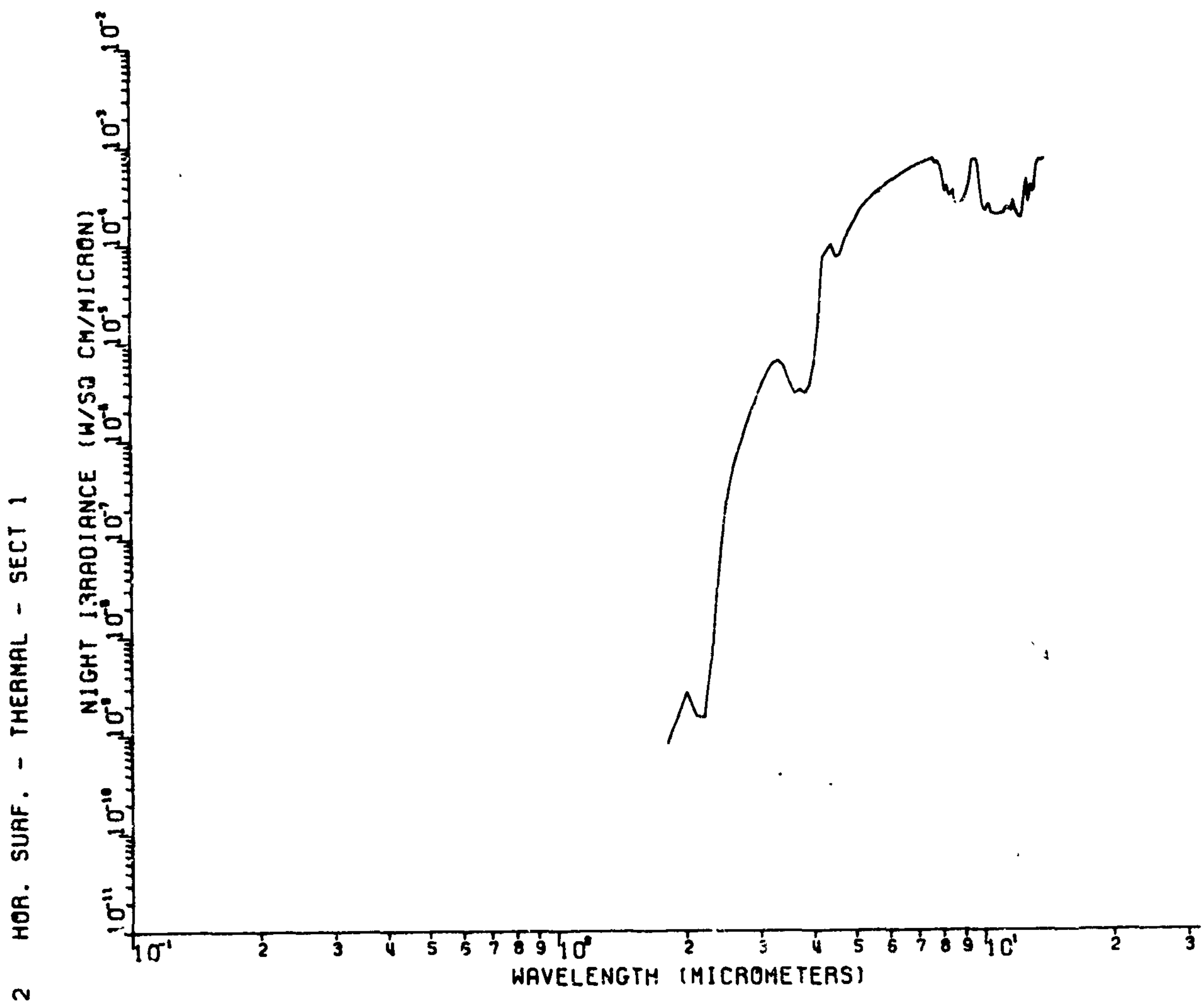


Figure 160. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 1, Zenith Angle of 18.1°

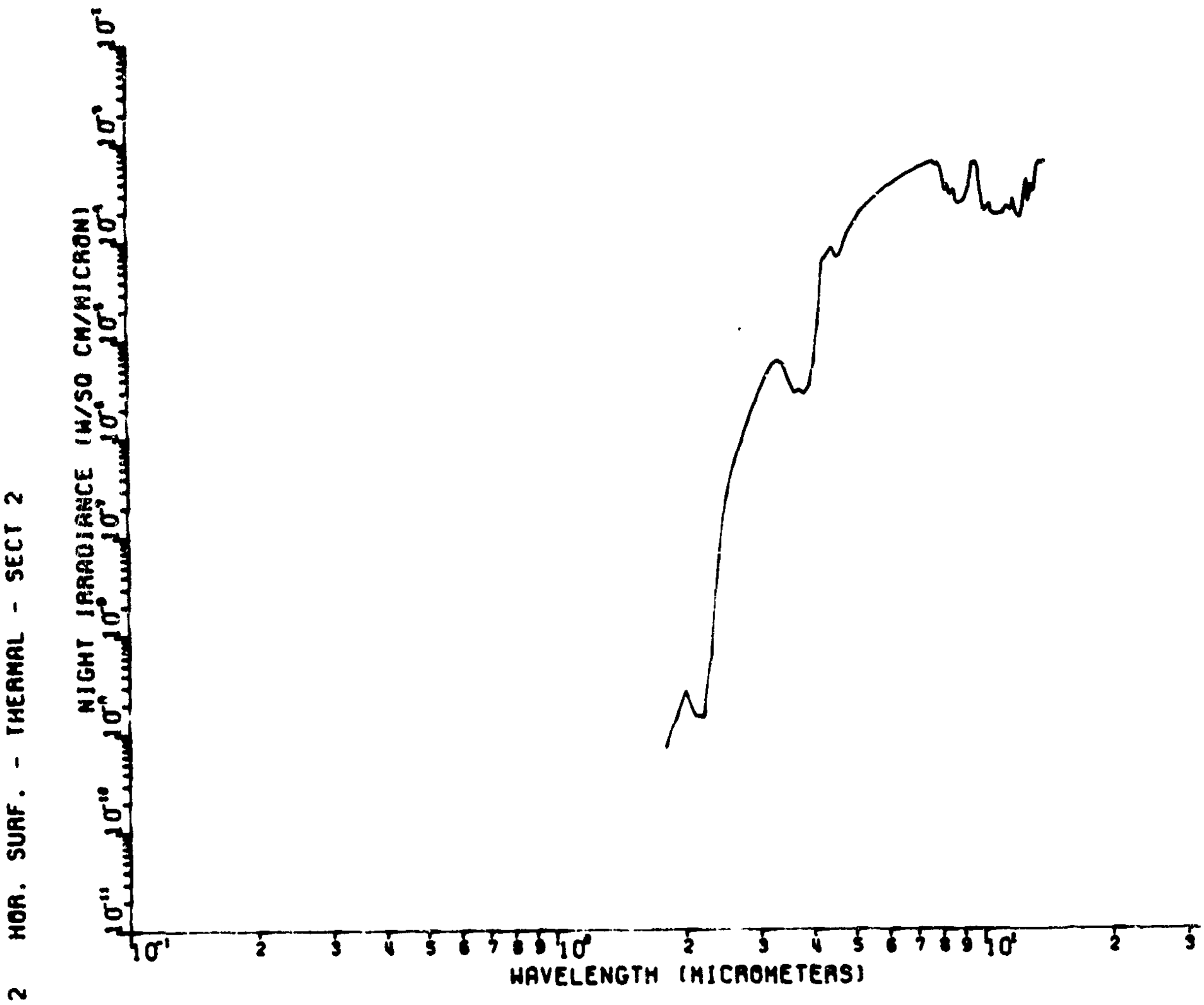


Figure 161. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 2, Zenith Angle of 31.7°

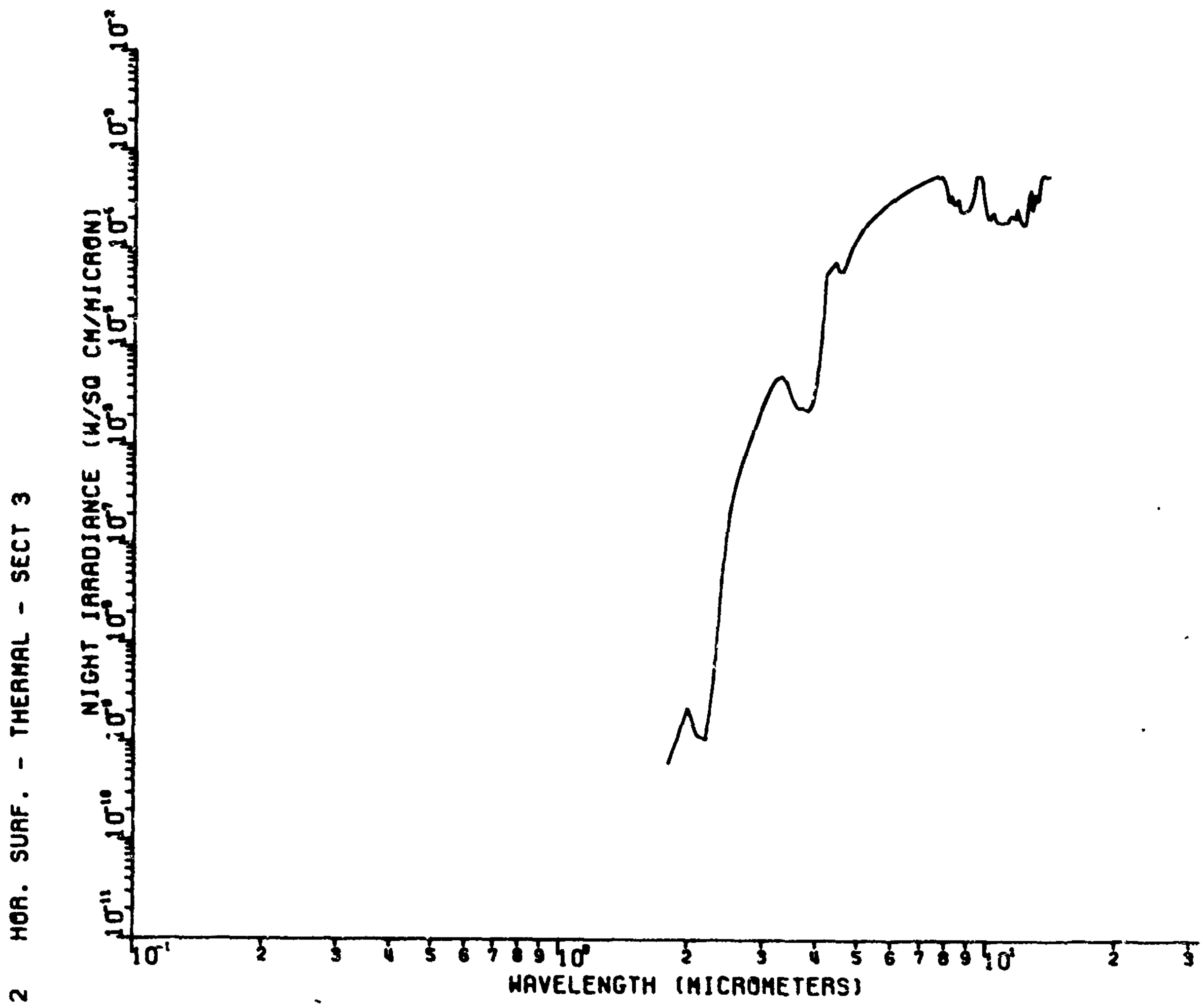


Figure 162. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 3, Zenith Angle of 41.4°

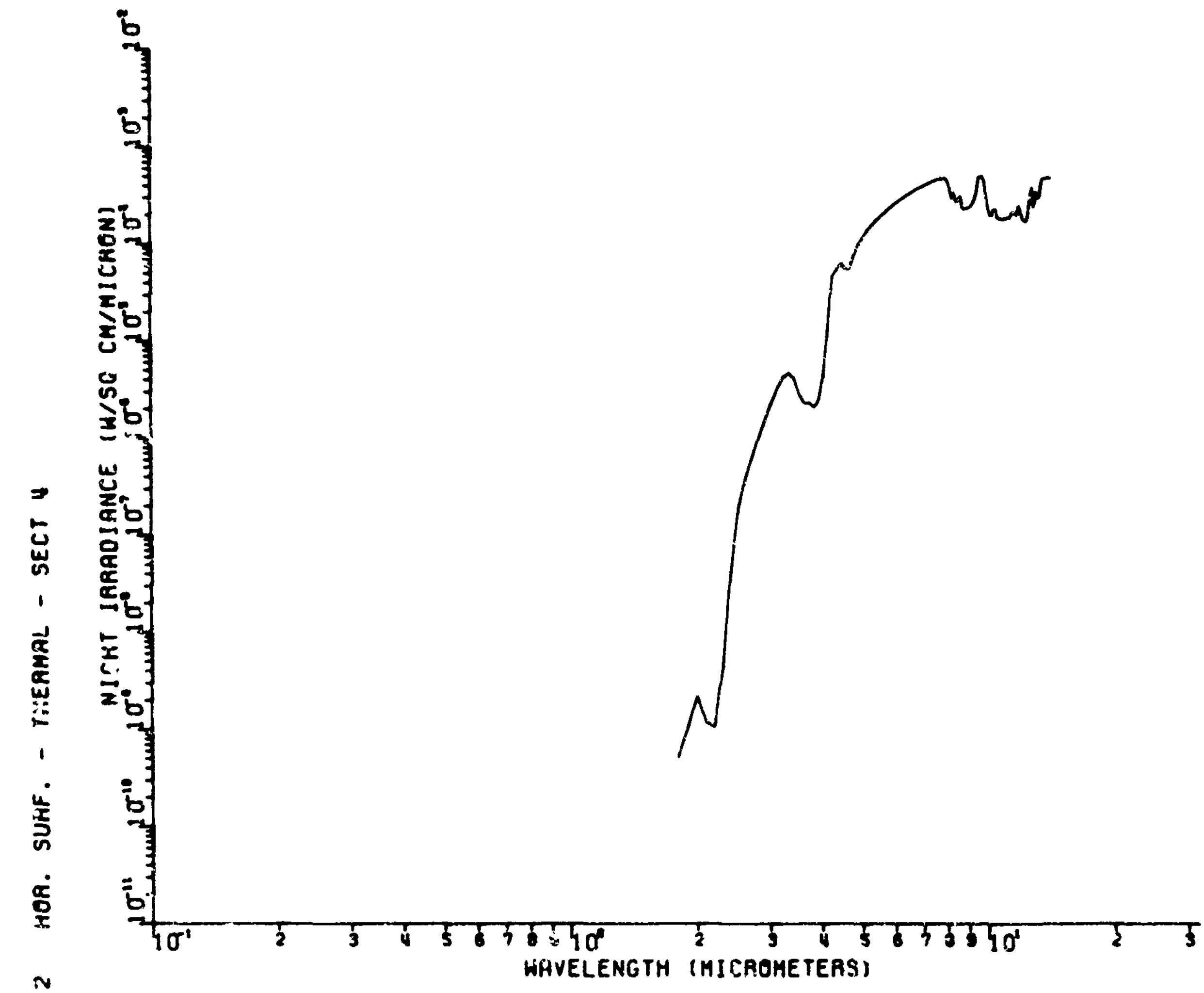


Figure 163. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 4, Zenith Angle of 49.5°

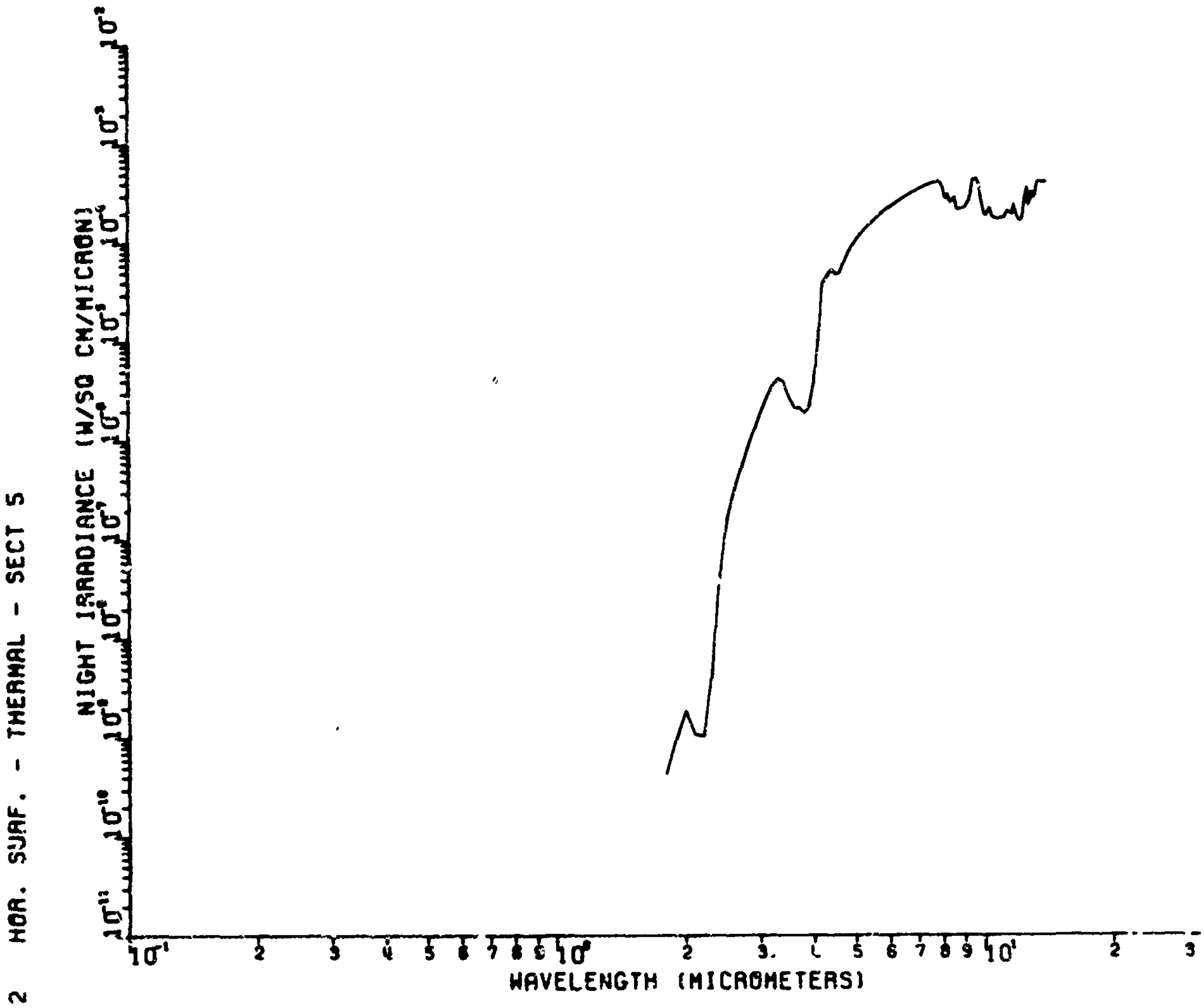


Figure 164. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 5, Zenith Angle of 56.6°

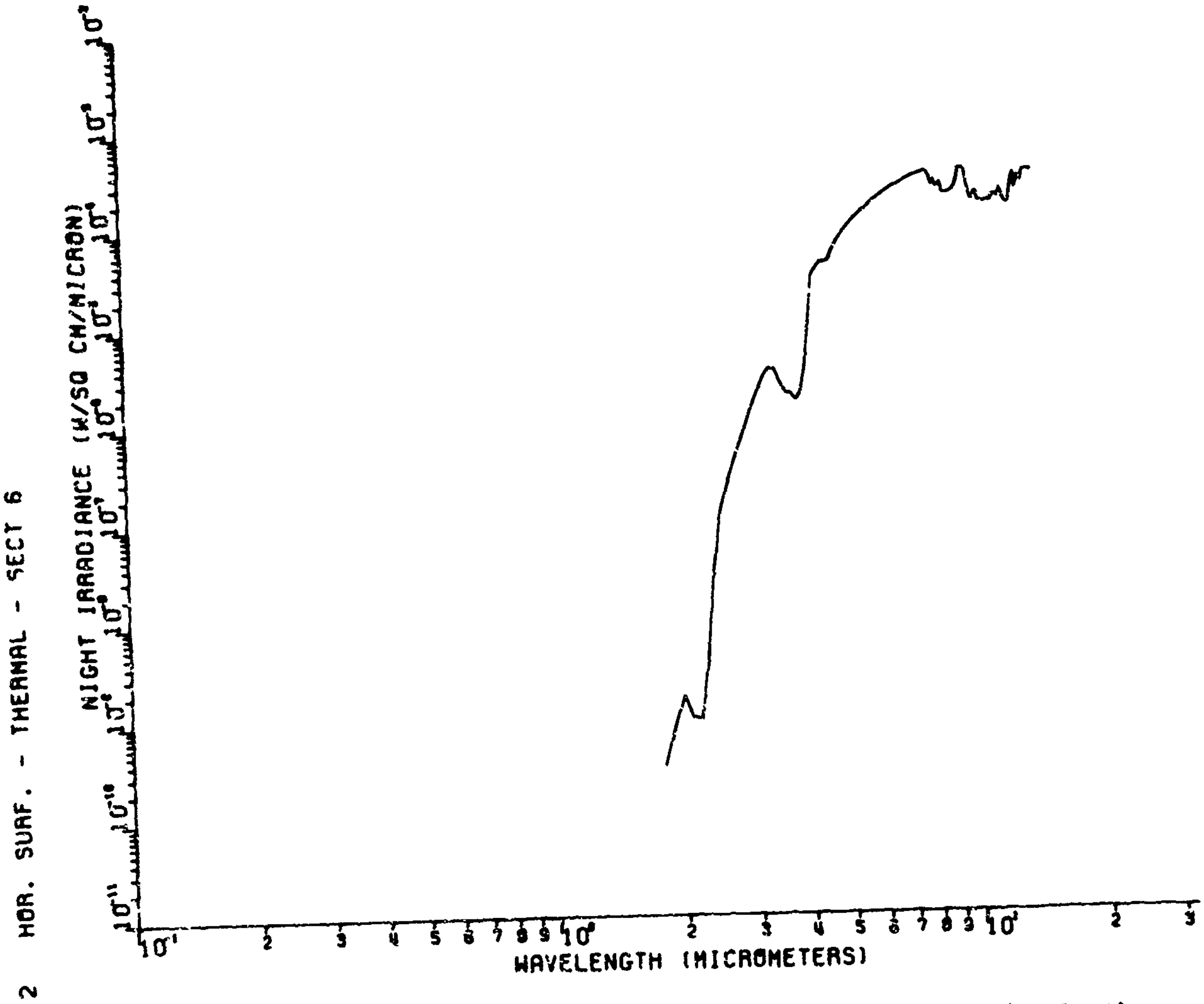


Figure 165. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 6, Zenith Angle of 63.2°

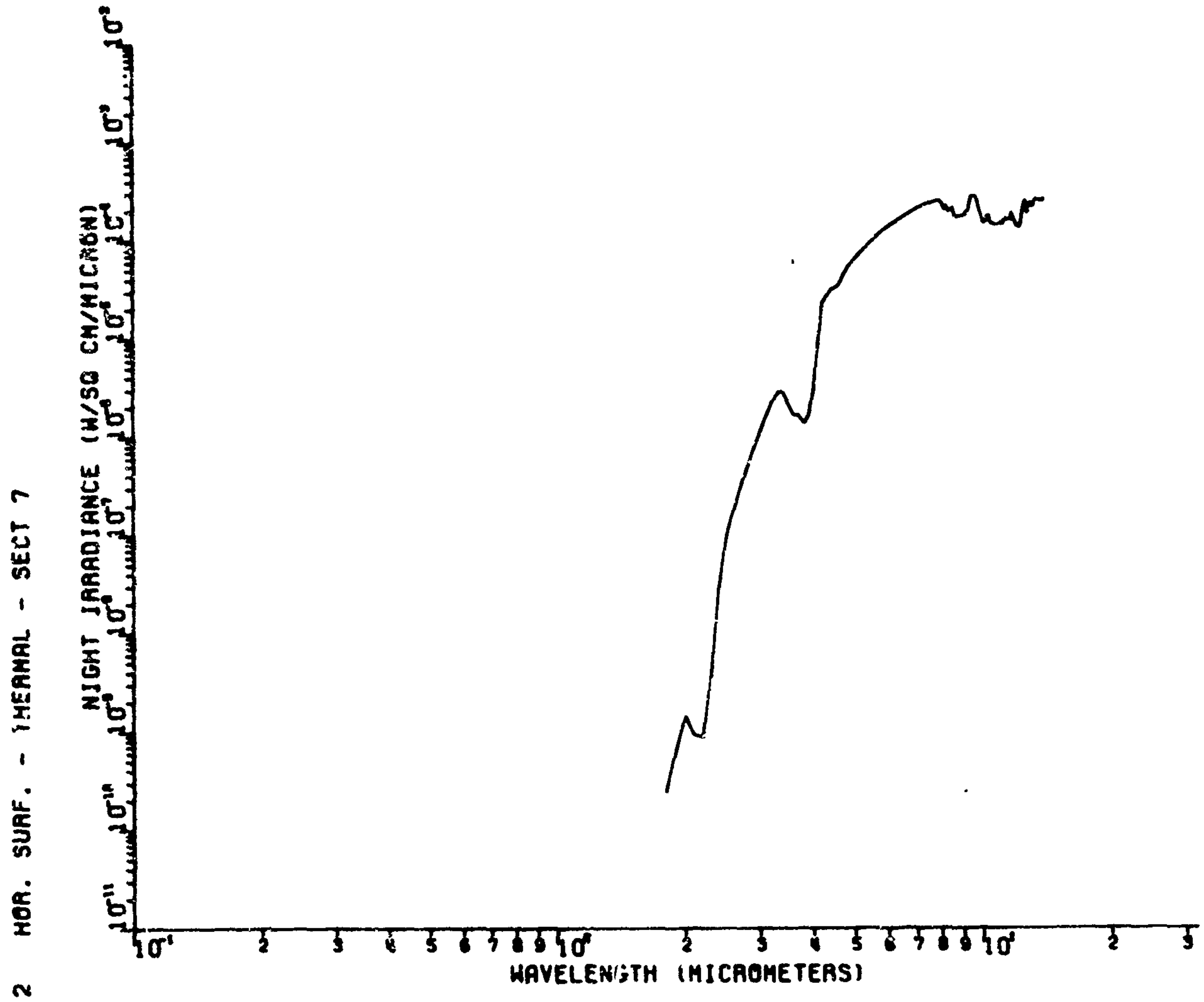


Figure 166. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 7, Zenith Angle of 69.5°

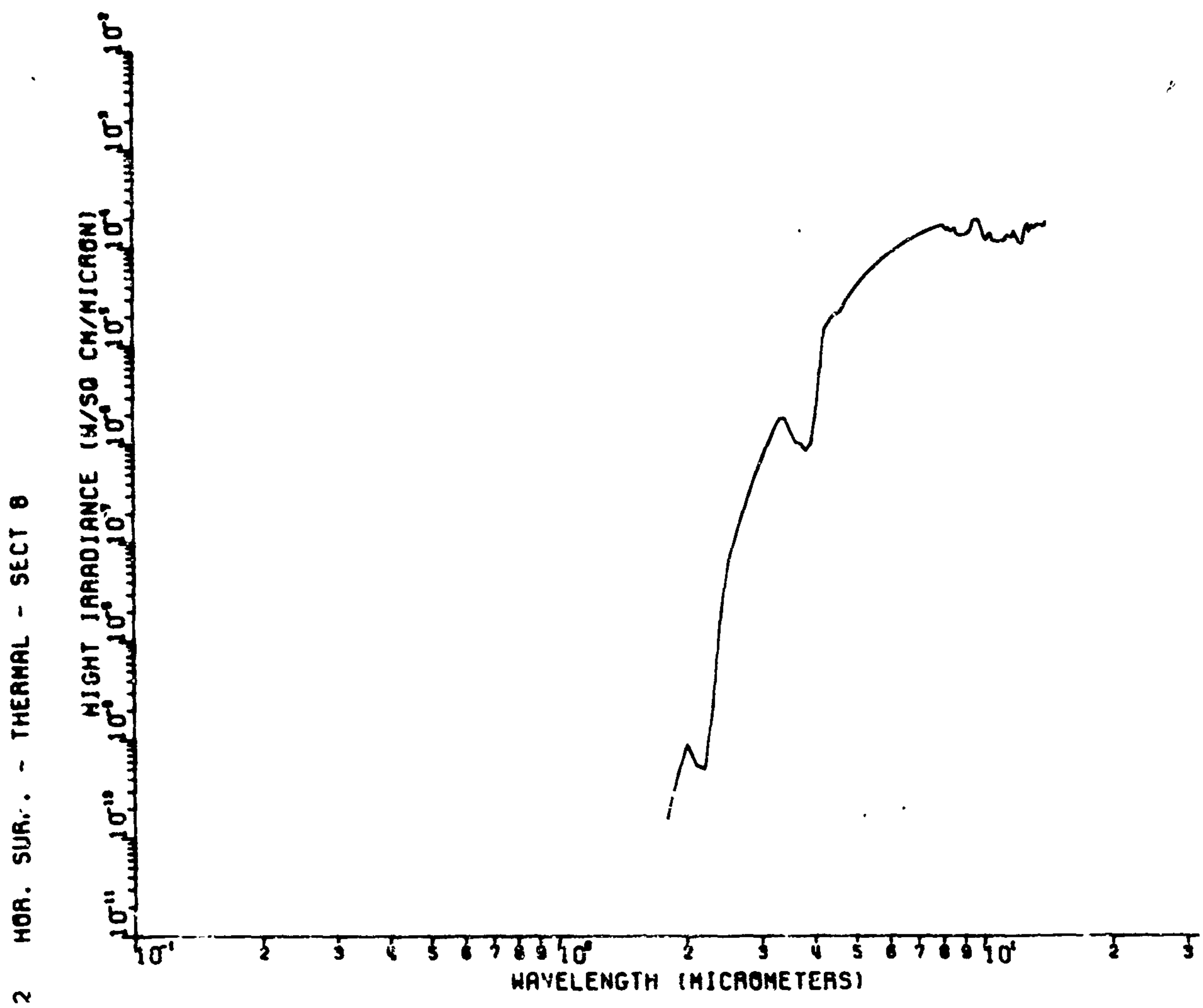


Figure 167. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 8, Zenith Angle of 75.5°

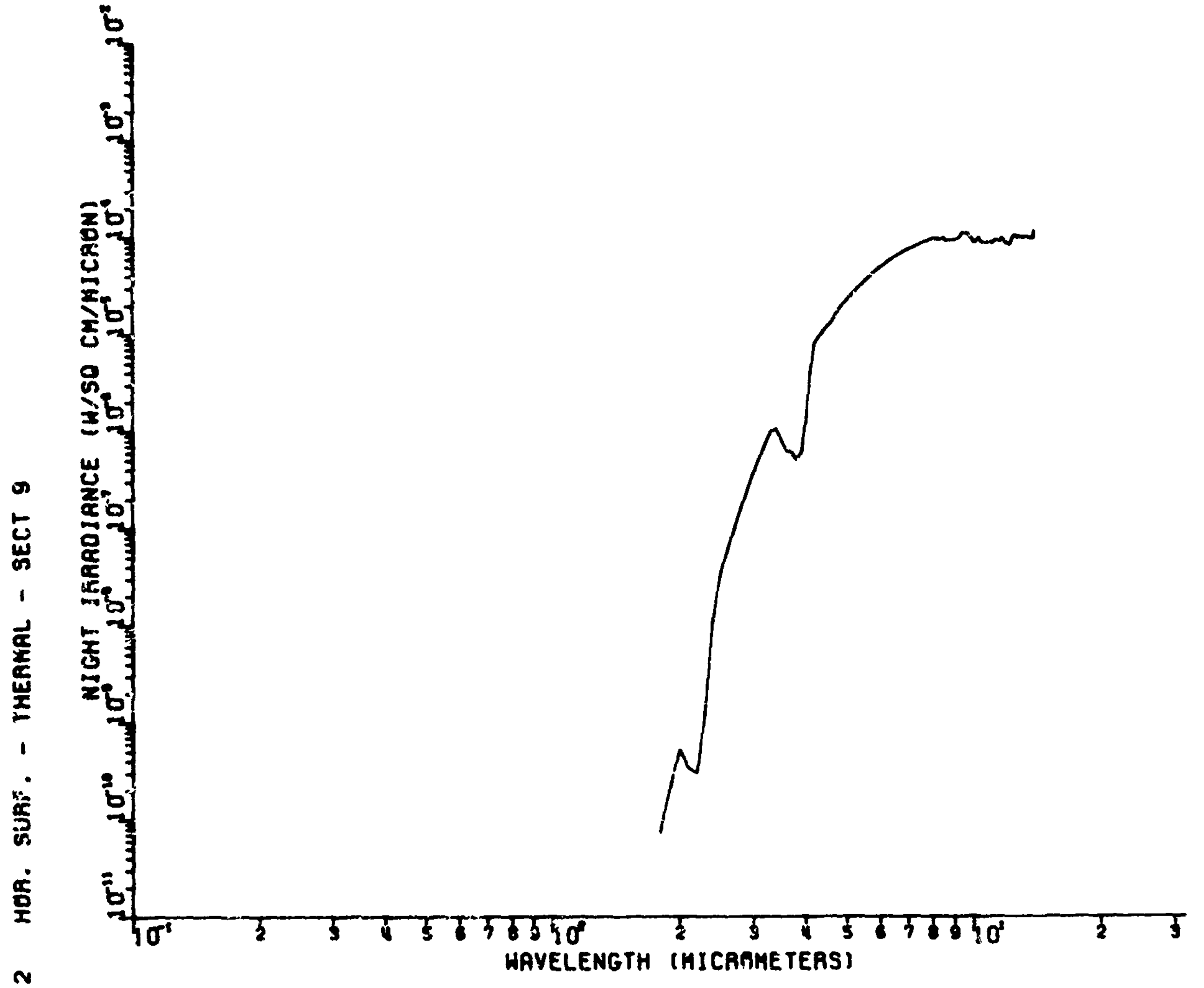


Figure 168. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 9, Zenith Angle of 81.4°

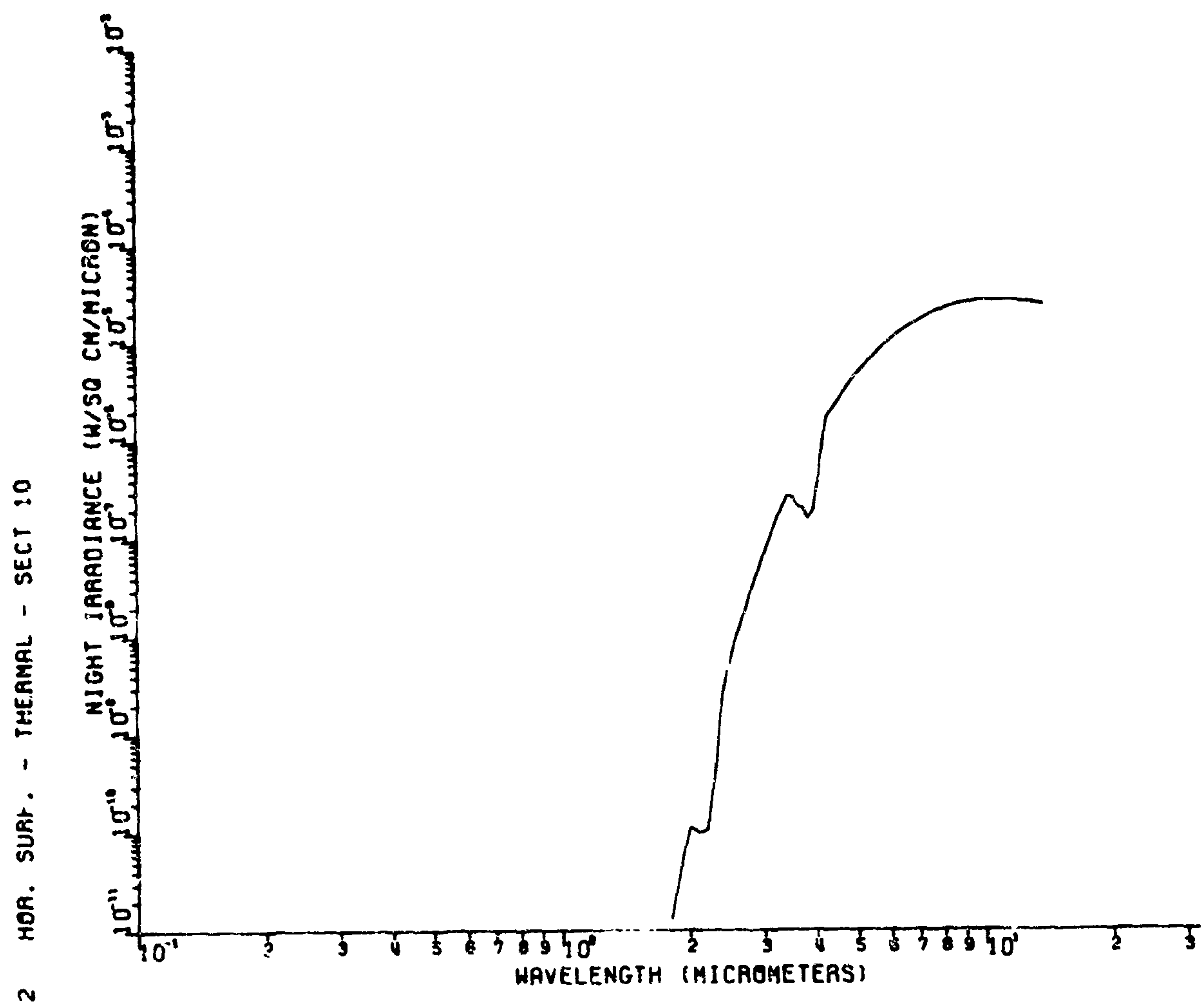


Figure 169. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Horizontal Surface, from Sky Segment 10, Zenith Angle of 87.2°

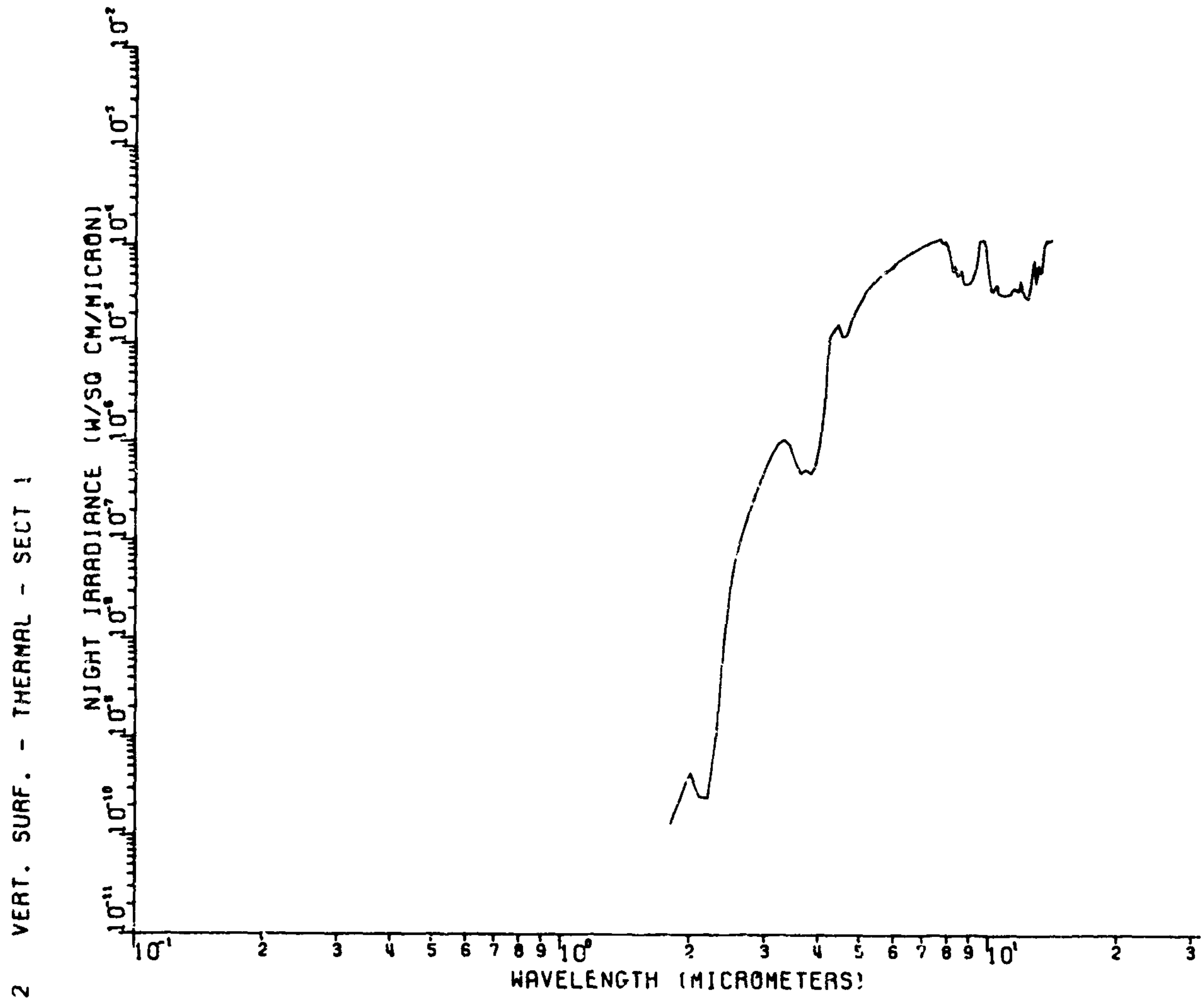


Figure 170. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 1, Zenith Angle of 18.1°

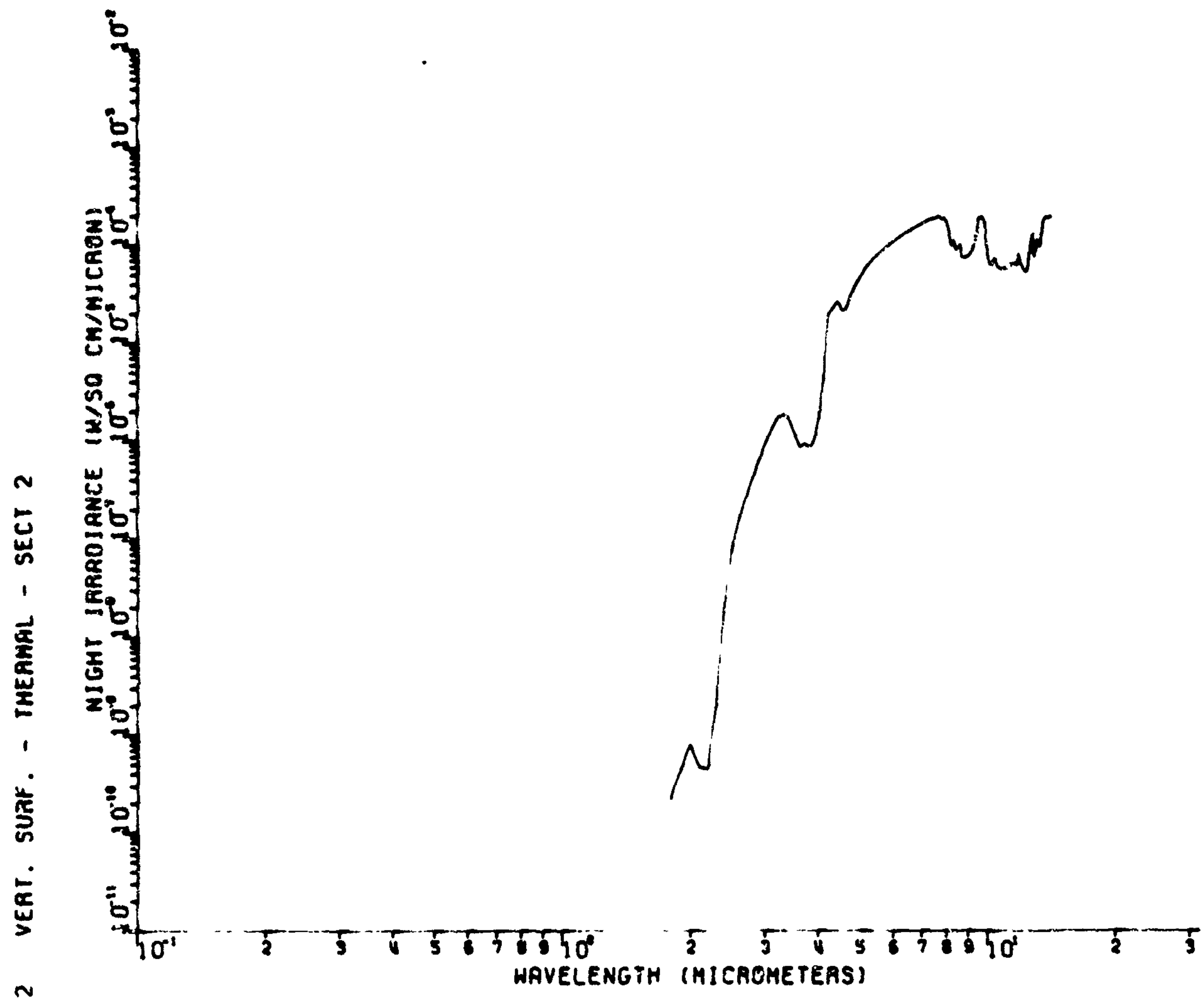


Figure 171. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 2, Zenith Angle of 31.7°

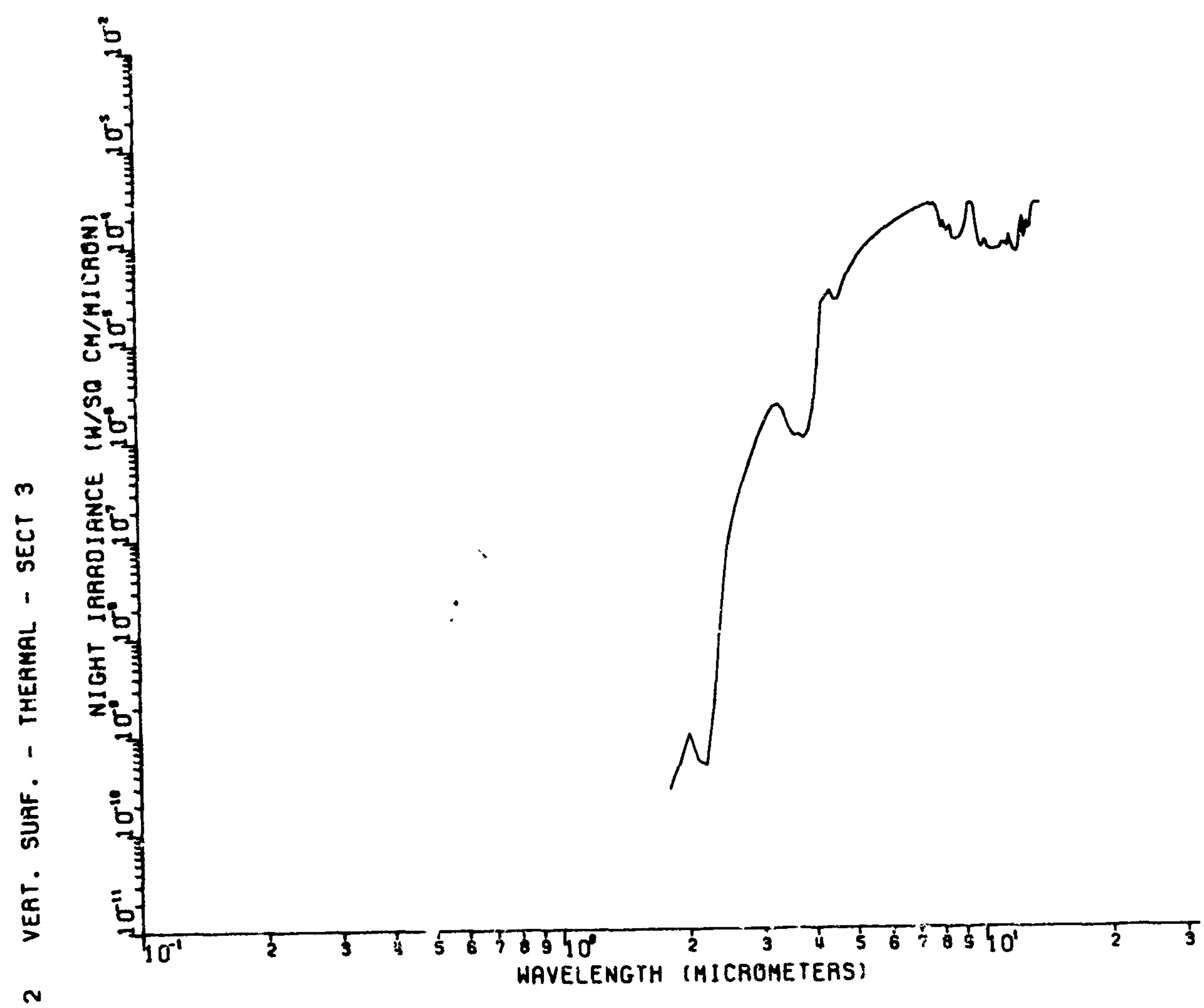


Figure 172. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 3, Zenith Angle of 41.4°

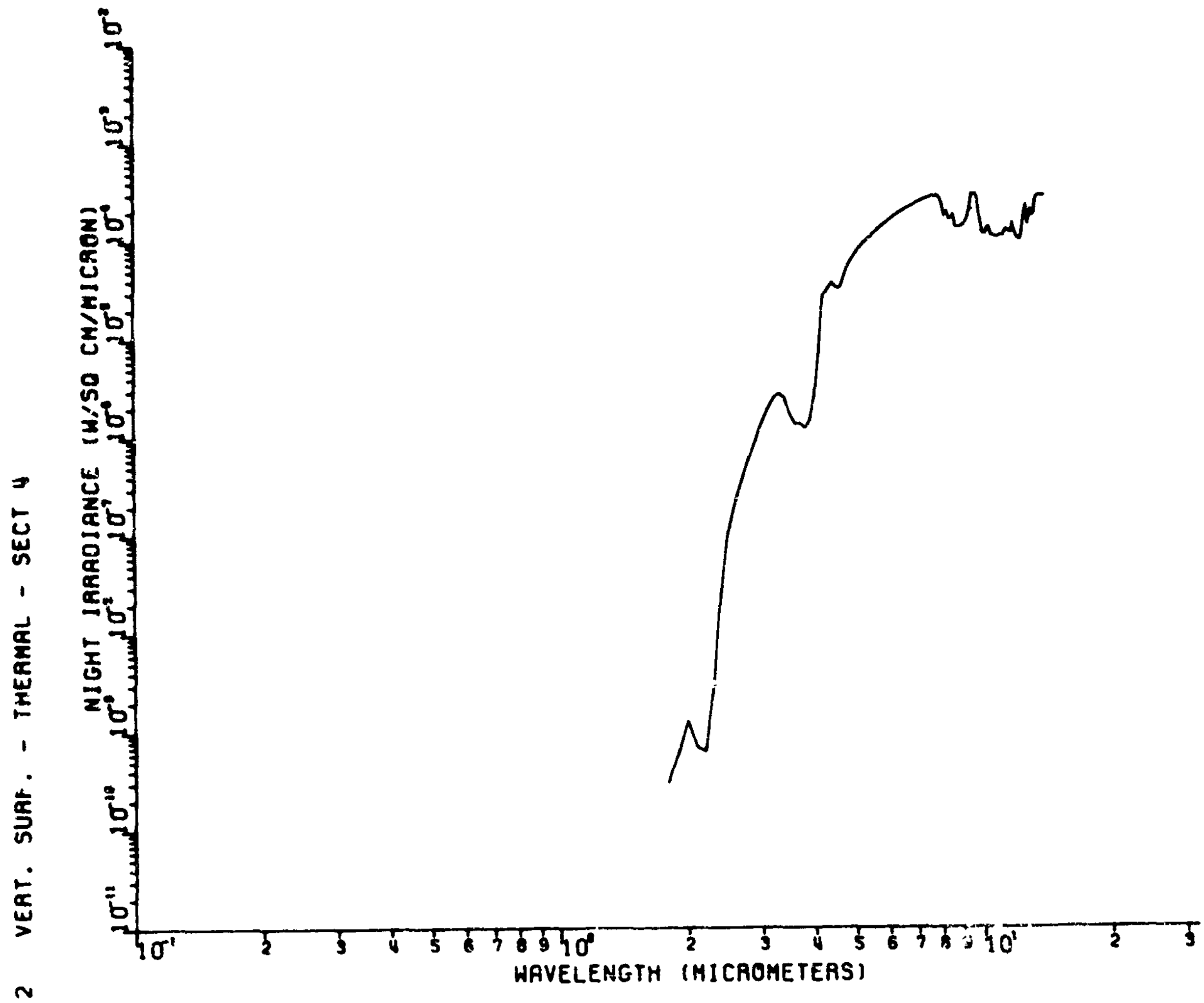


Figure 173. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 4, Zenith Angle of 49.5°

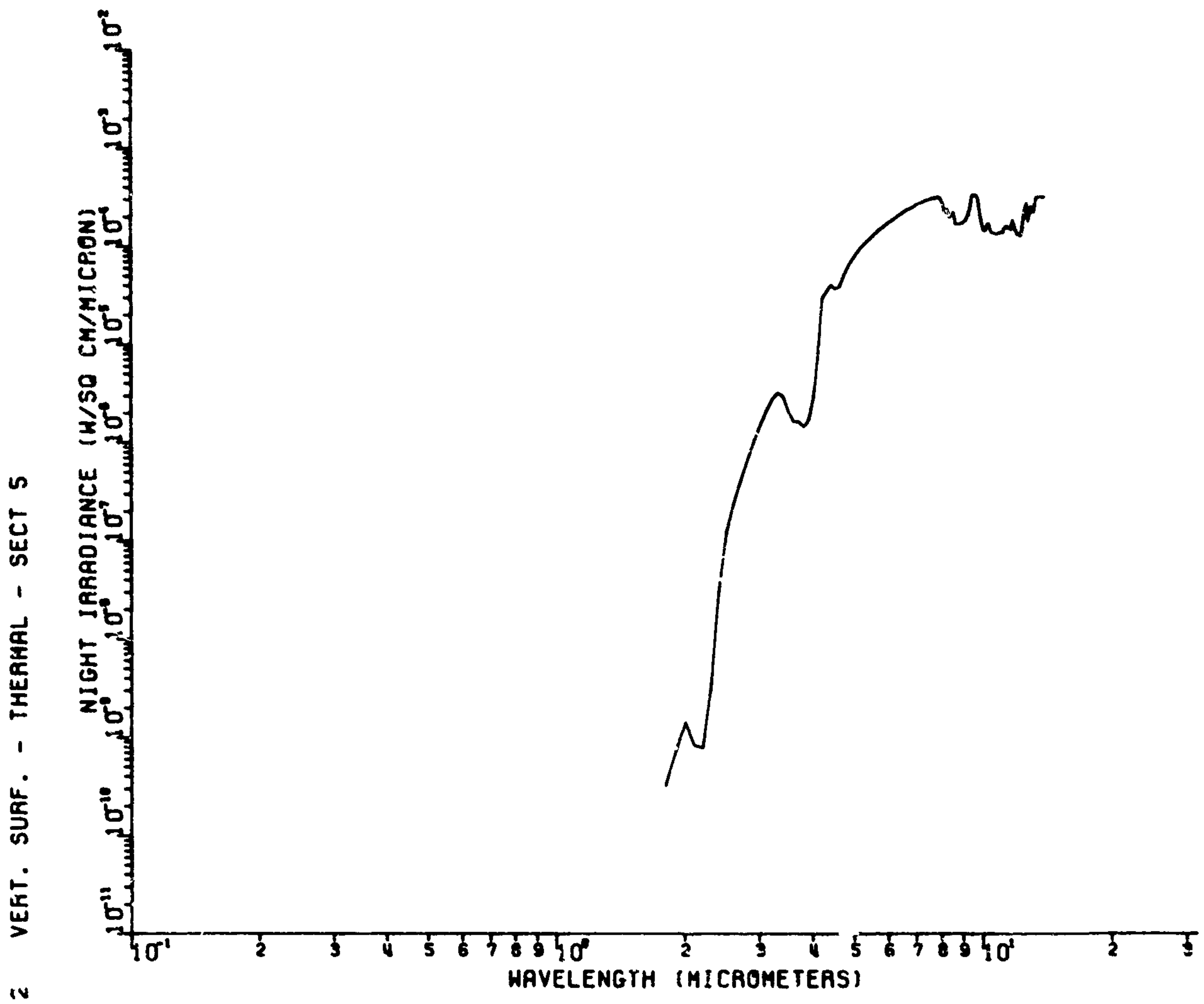


Figure 174. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 5, Zenith Angle of 56.6°

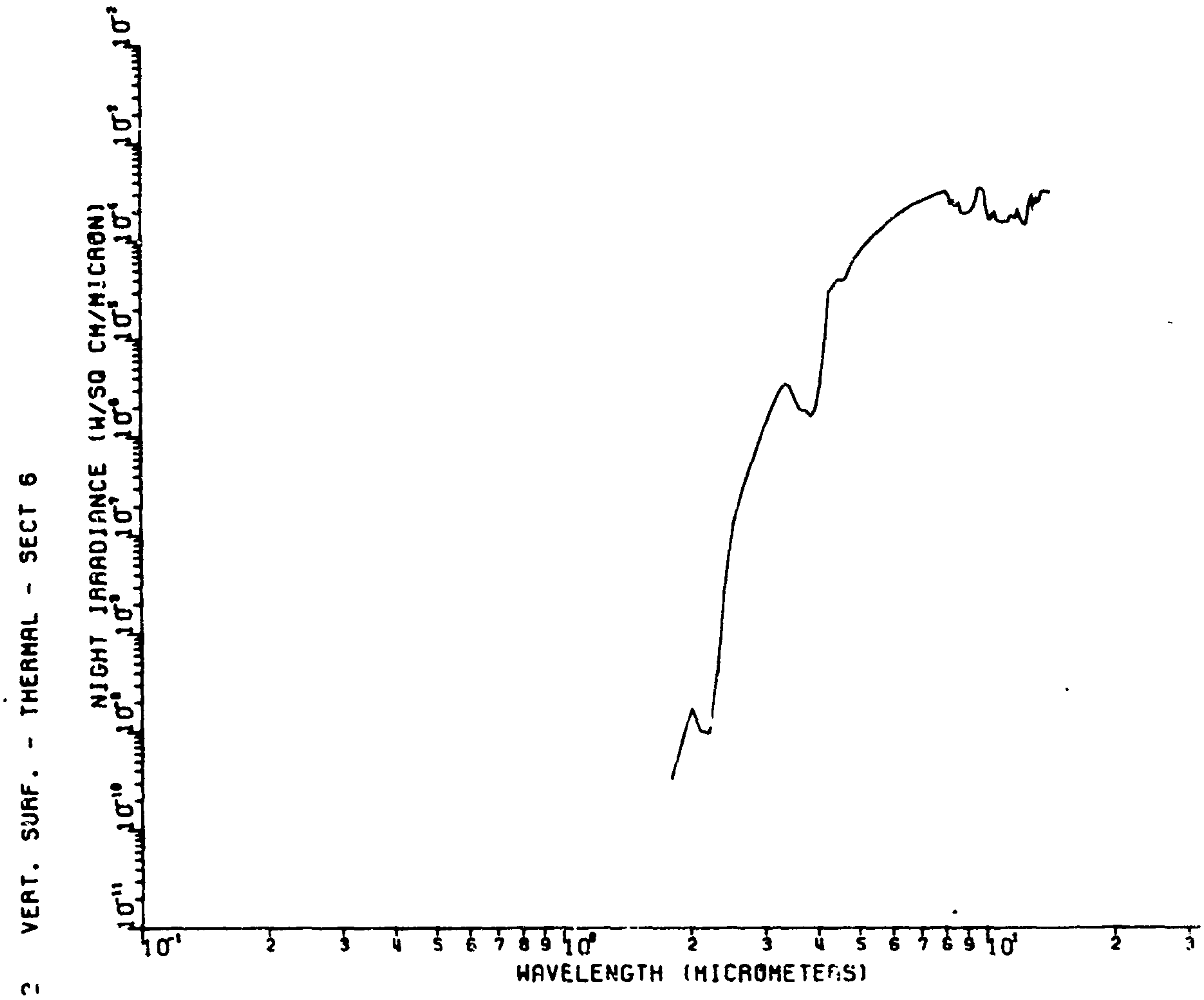


Figure 175. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 6, Zenith Angle of 63.2°

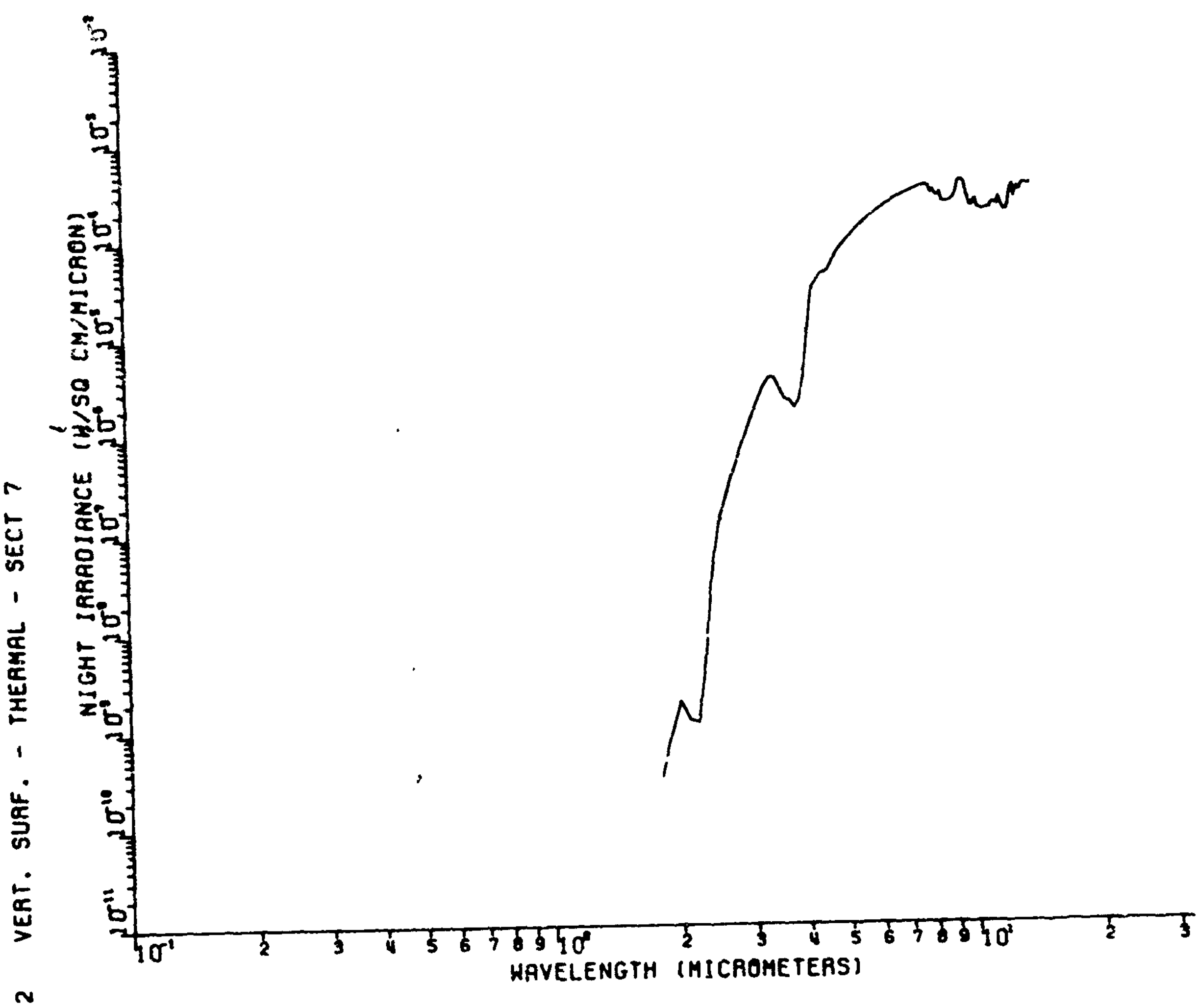


Figure 176. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 7, Zenith Angle of 69.5°

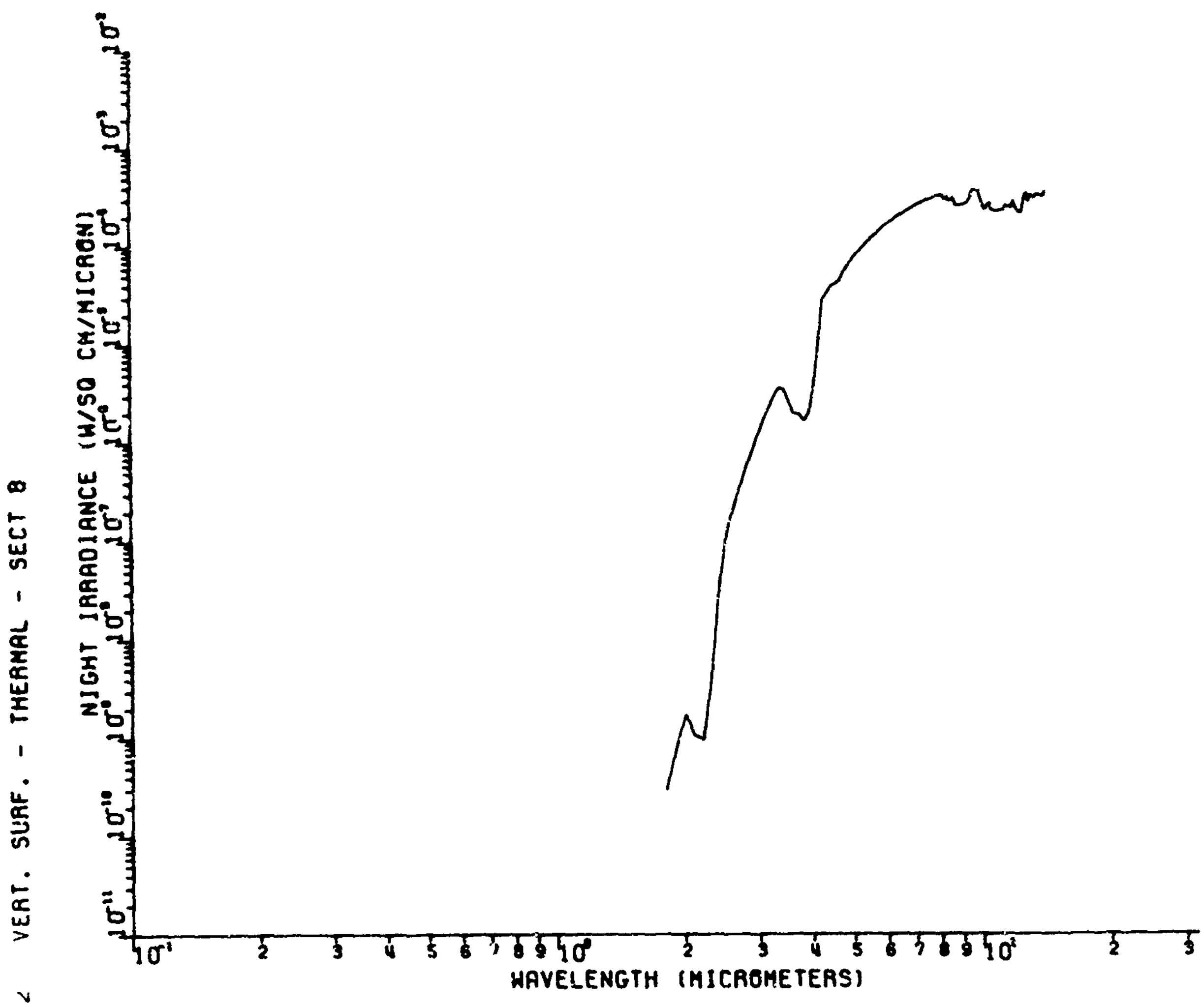


Figure 177. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 8, Zenith Angle of 75.5°

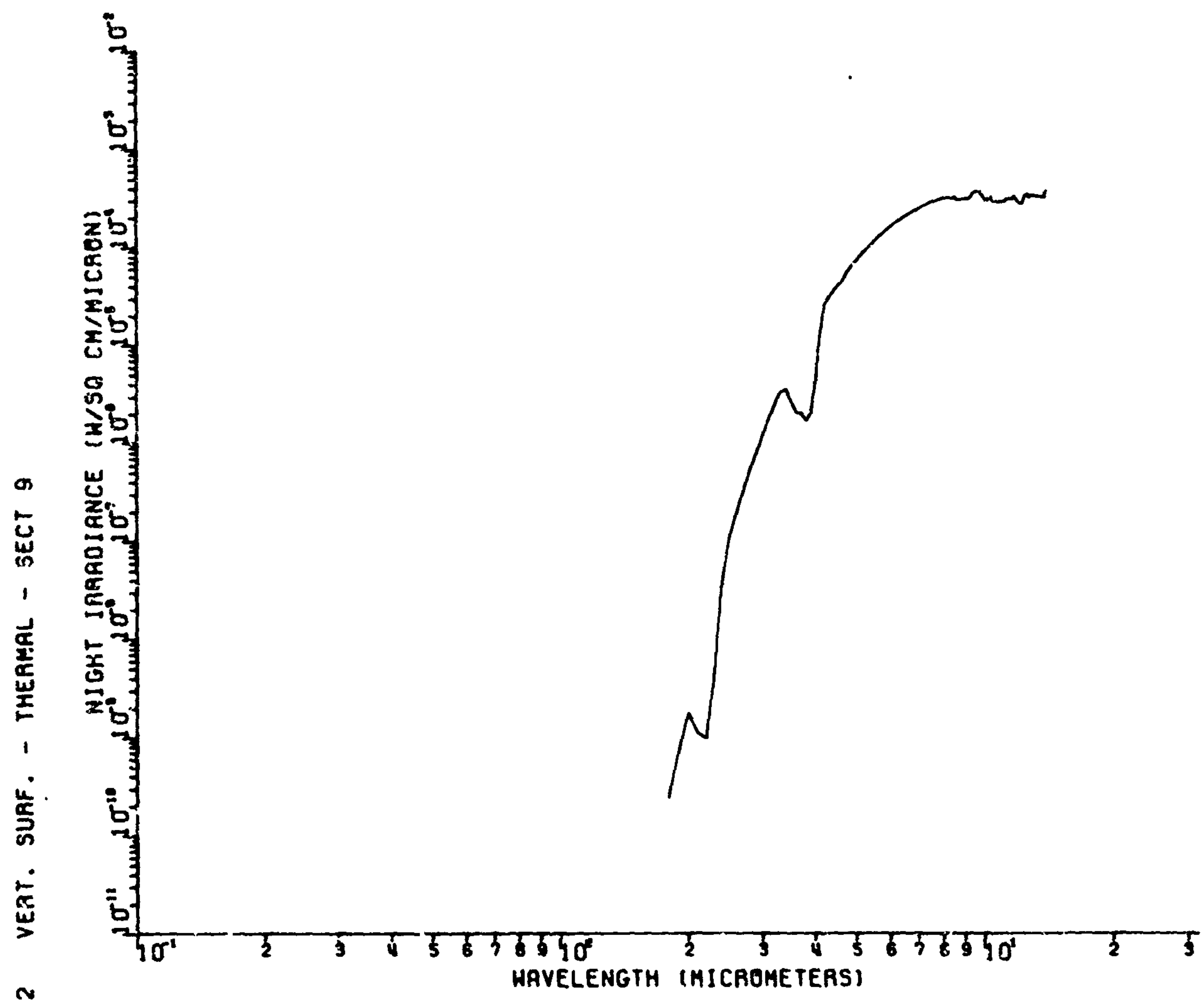


Figure 178. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 9, Zenith Angle of 81.4°

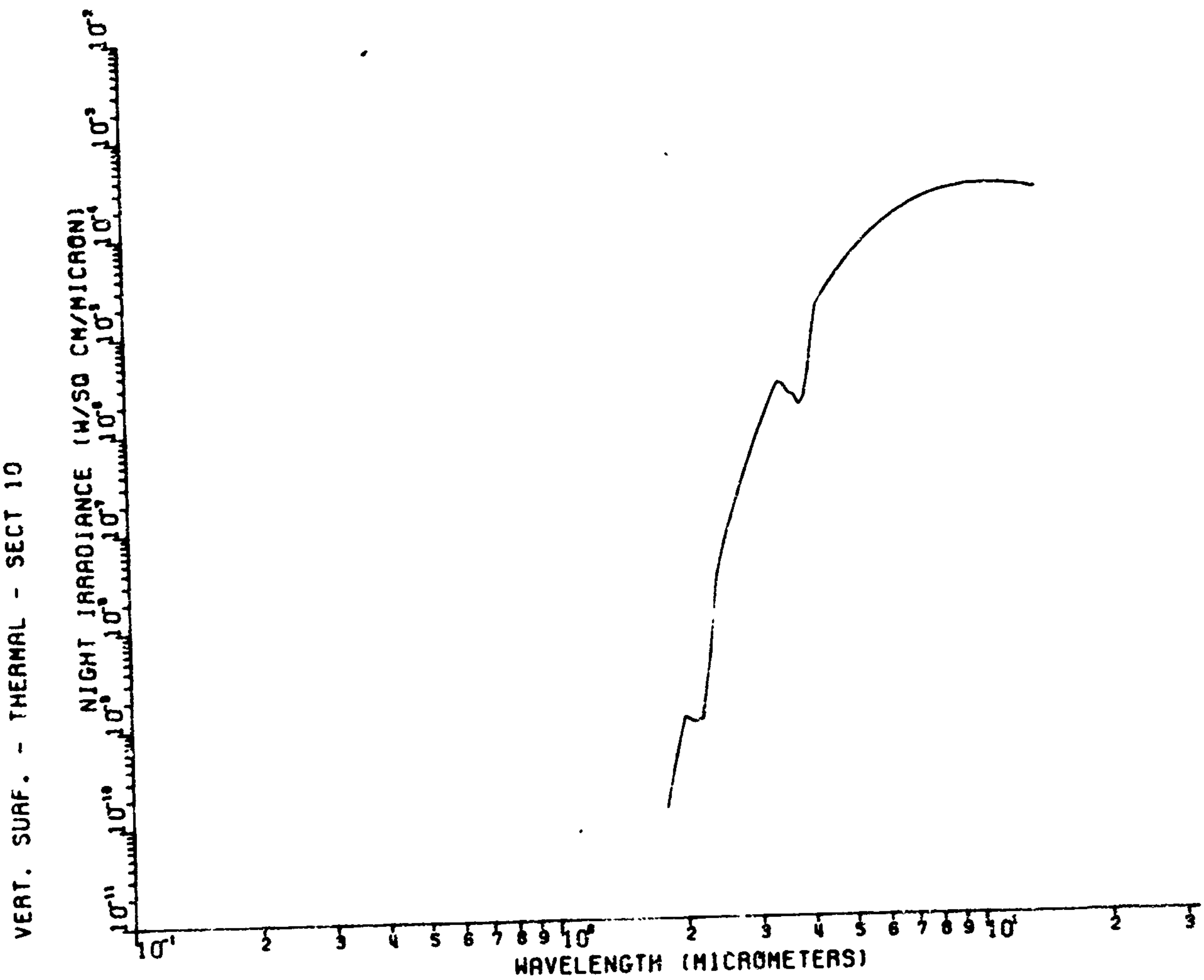


Figure 179. Tropospheric Thermal Energy for 0.1 of the Sky Illuminating a Vertical Surface, from Sky Segment 10, Zenith Angle of 87.2°

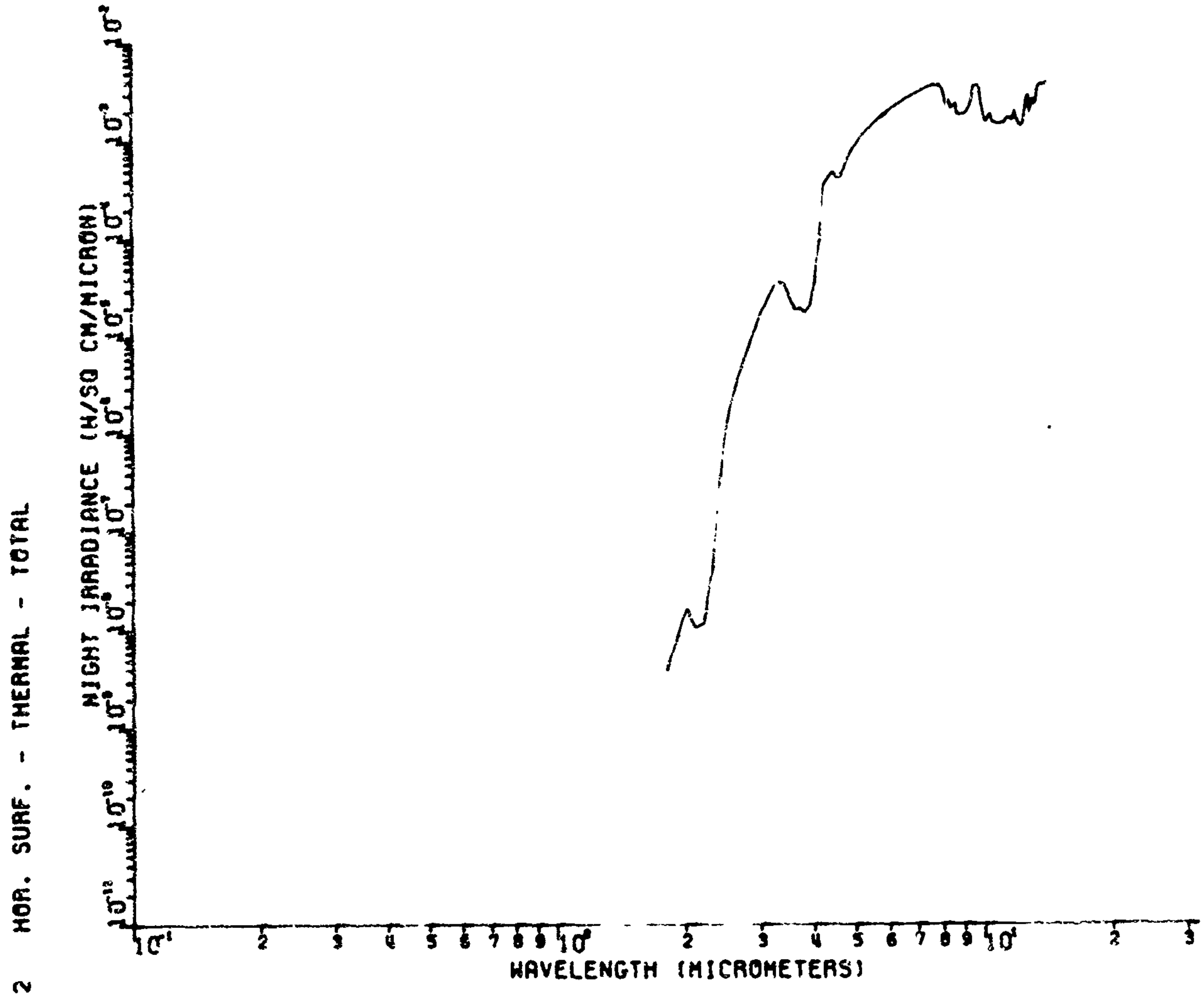


Figure 180. Total Tropospheric Thermal Energy Illuminating a Horizontal Surface

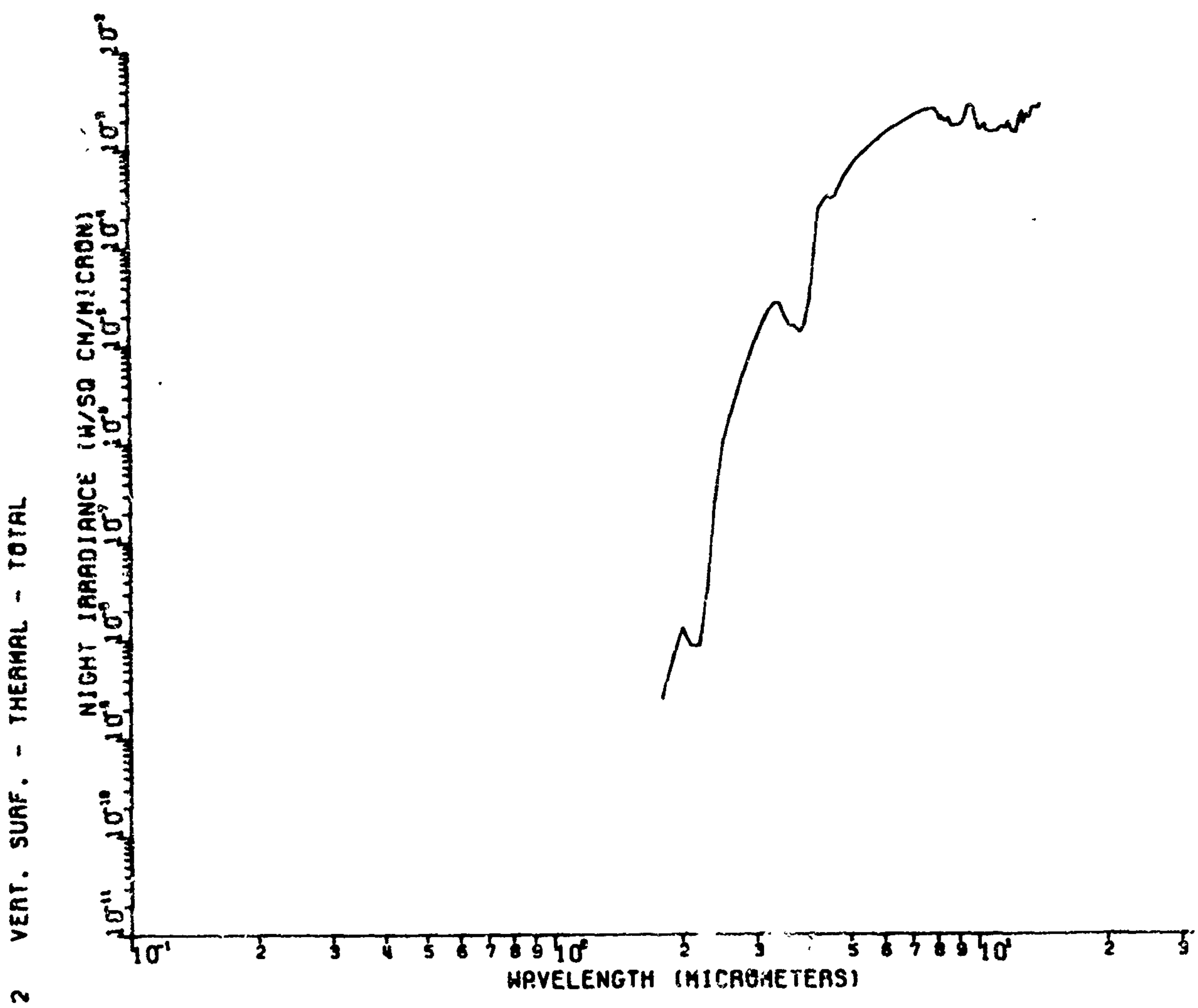


Figure 181. Total Tropospheric Thermal Energy Illuminating a Vertical Surface

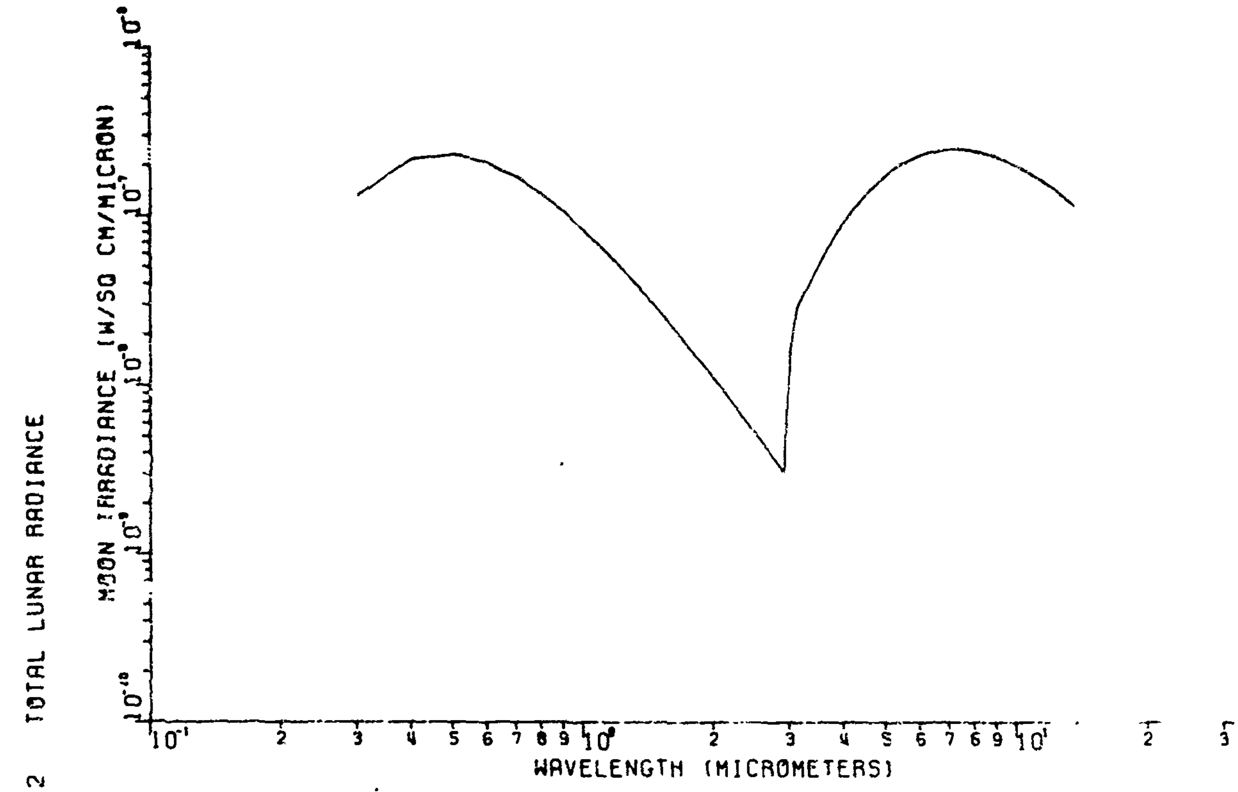


Figure 182. Full Moon Irradiance Above the Atmosphere

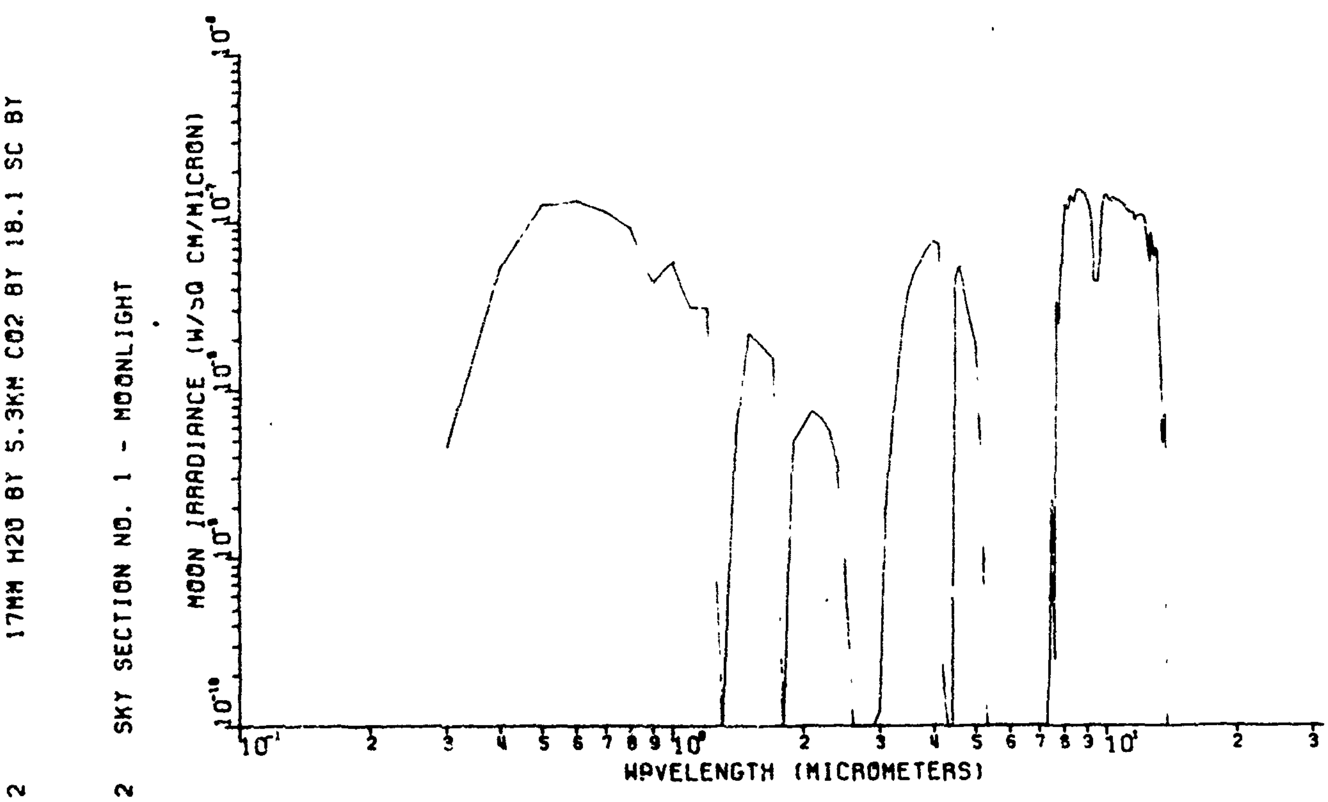


Figure 183. Full Moon Irradiance When Moon is at a Zenith Angle of 18.1°

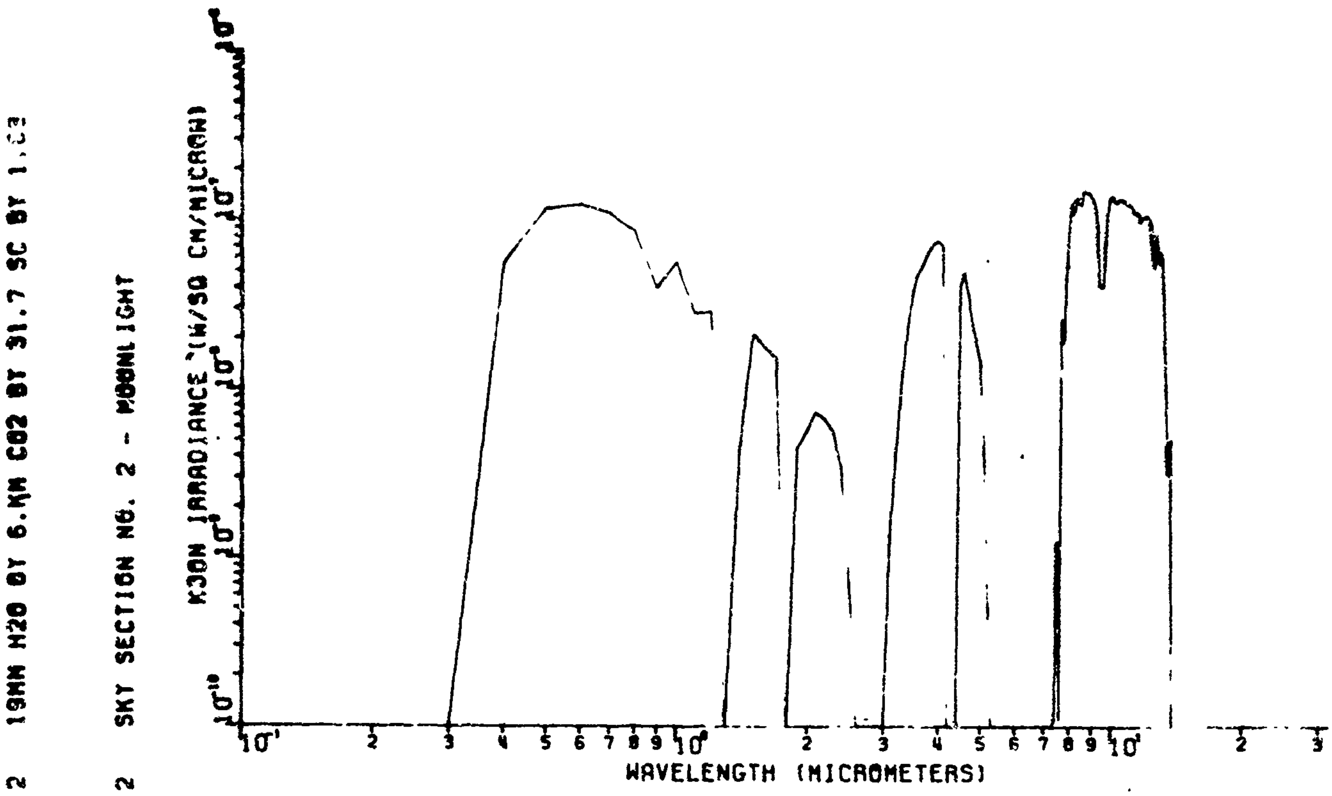


Figure 184. Full Moon Irradiance When Moon is at a Zenith Angle of 31.7°

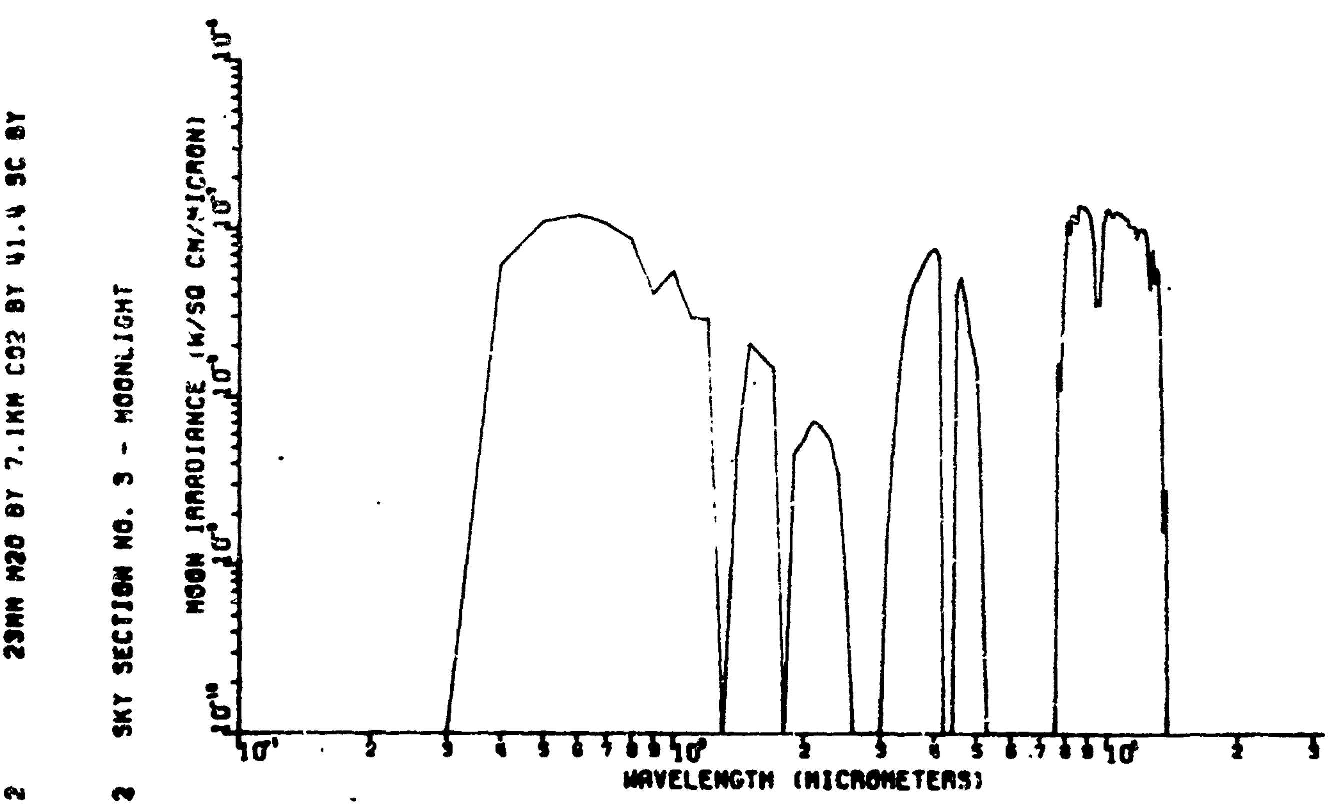


Figure 185. Full Moon Irradiance When Moon is at a Zenith Angle of 41.4°

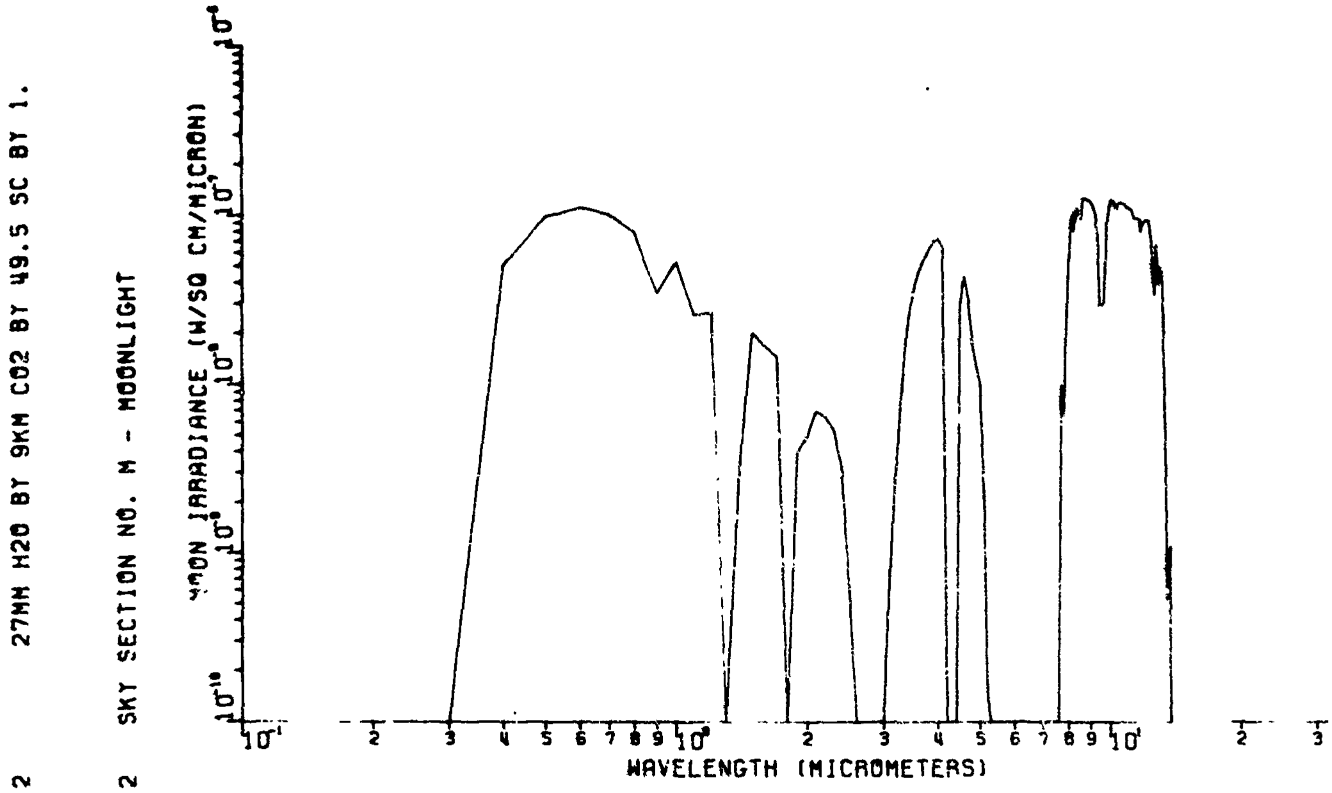


Figure 186. Full Moon Irradiance When Moon is at a Zenith Angle of 49.5°

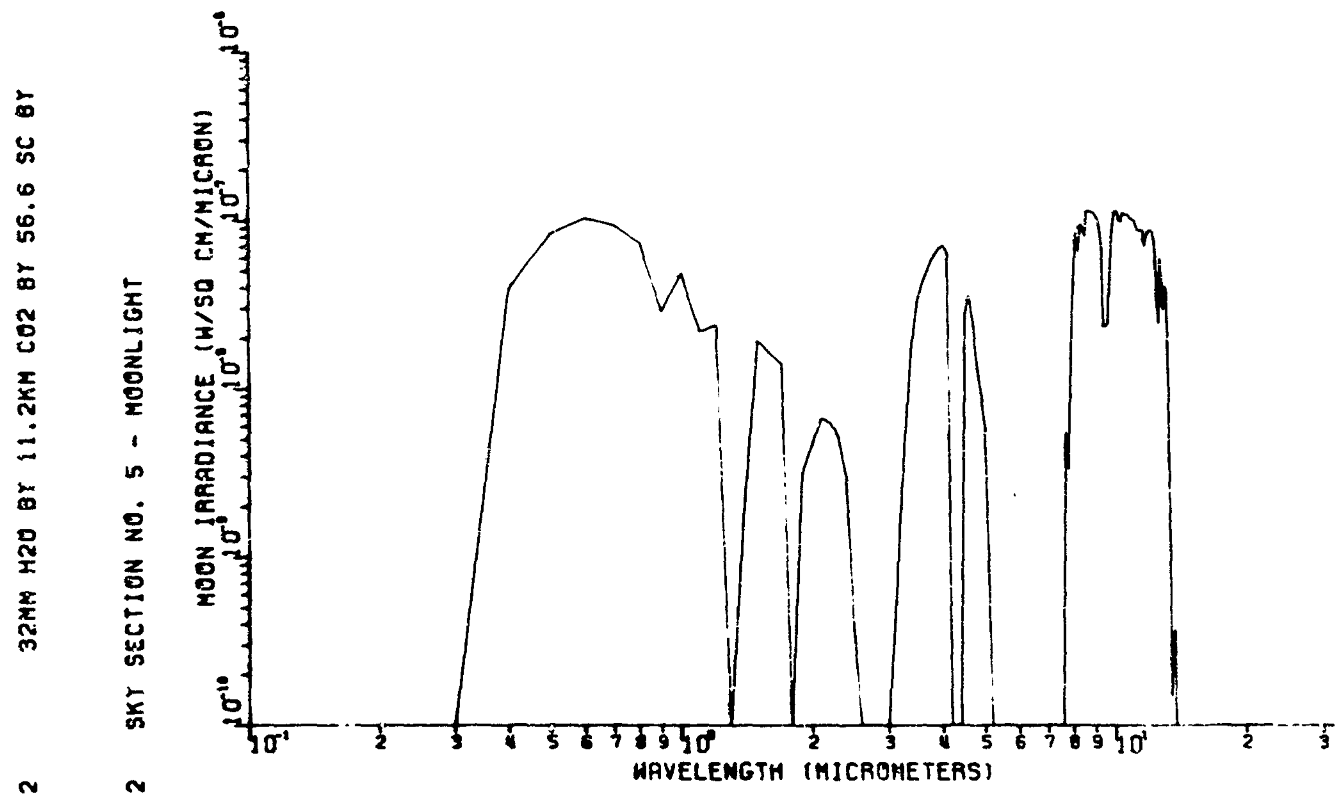


Figure 187. Full Moon Irradiance When Moon is at a Zenith Angle of 56.6°

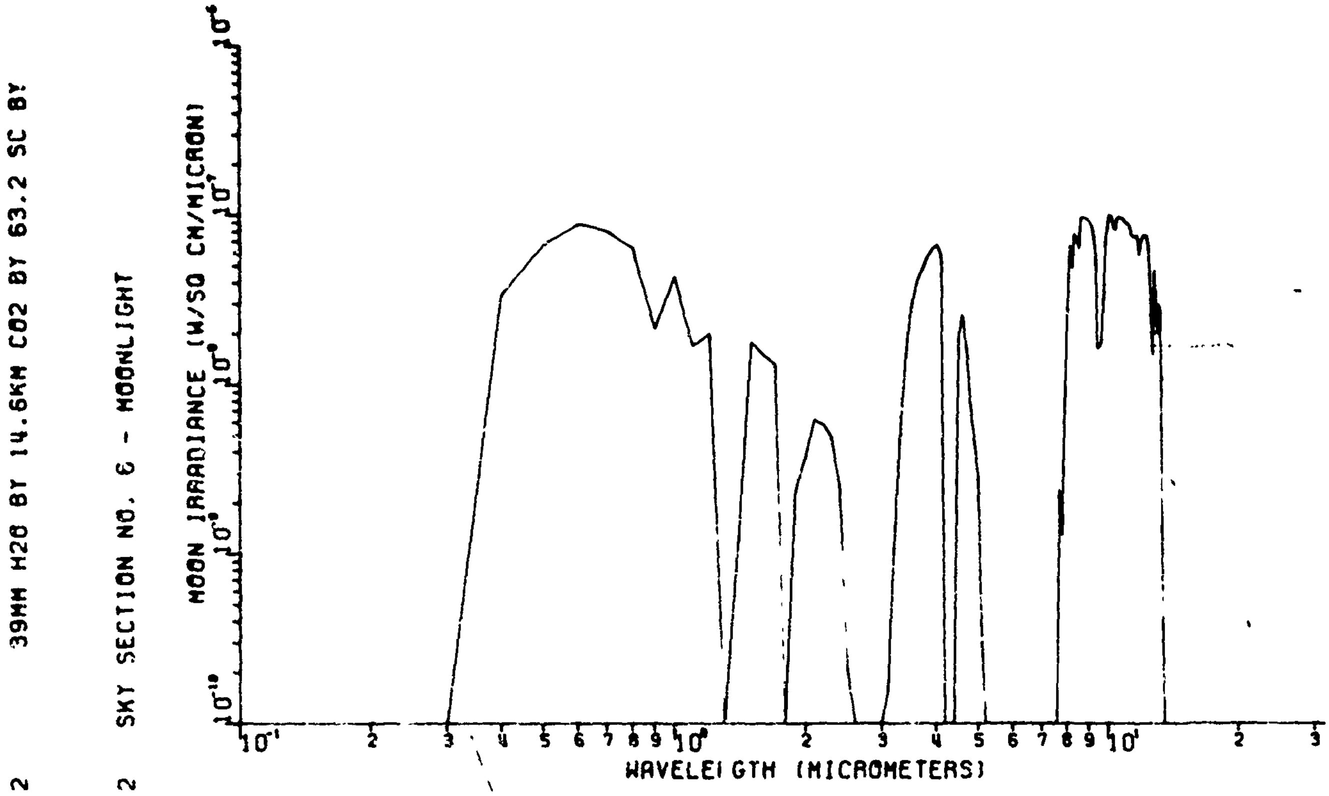


Figure 188. Full Moon Irradiance When Moon is at a Zenith Angle of 63.2°

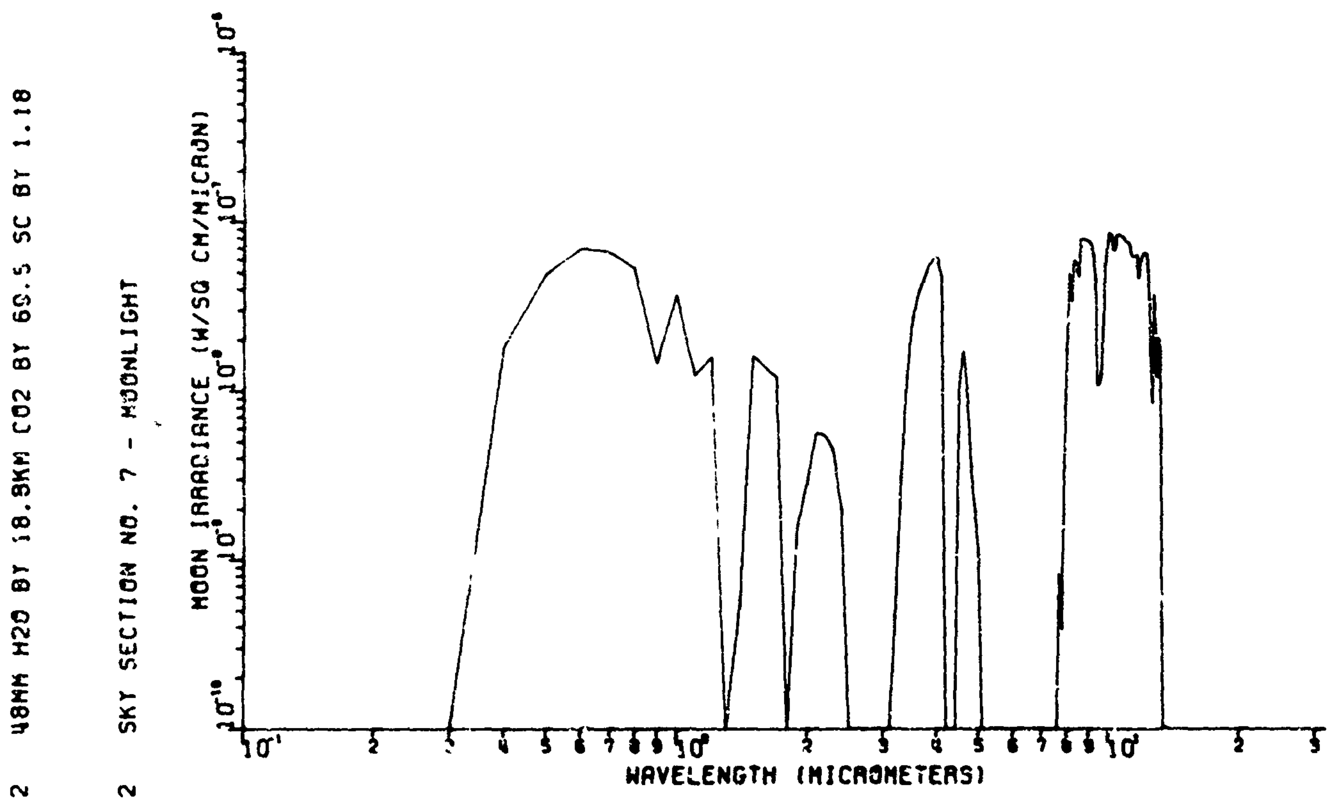


Figure 189. Full Moon Irradiance When Moon is at a Zenith Angle of 69.5°

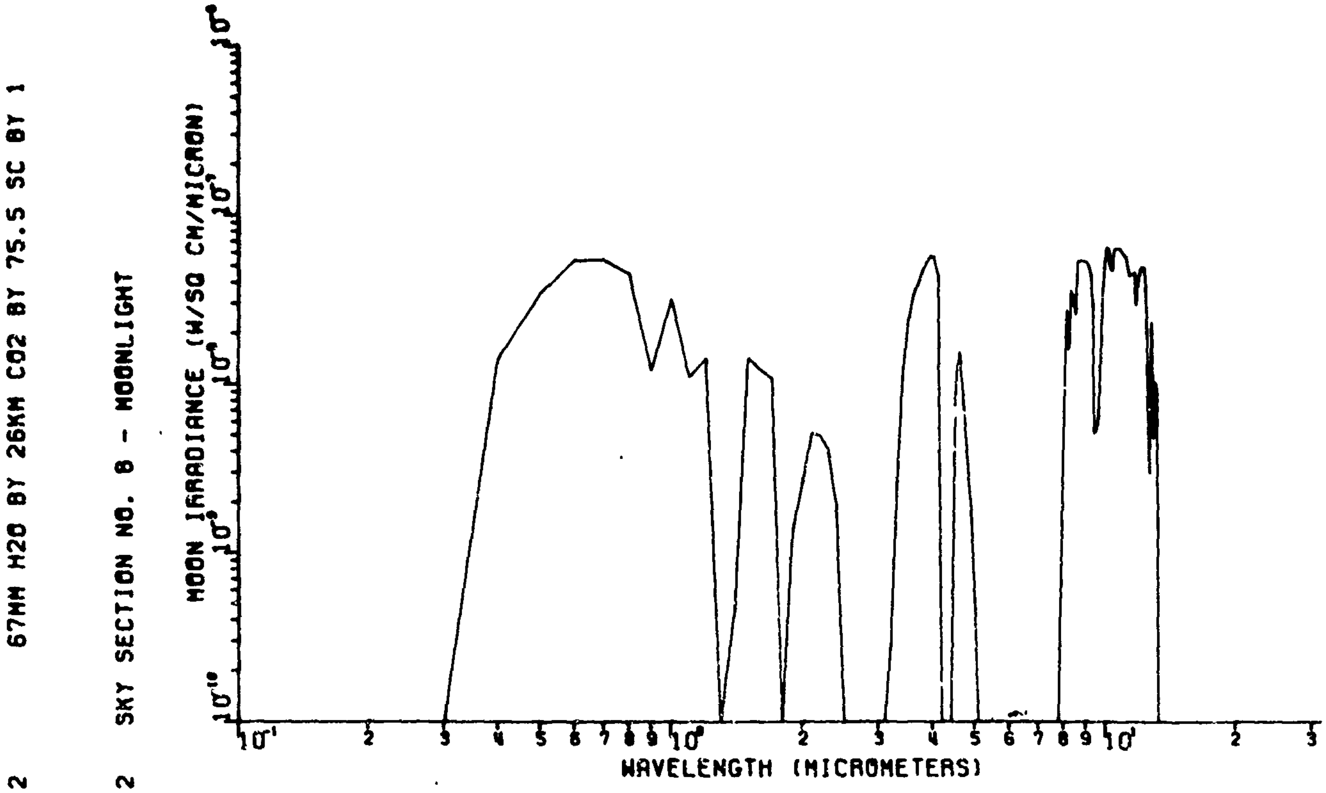


Figure 190. Full Moon Irradiance When Moon is at a Zenith Angle of 75.5°

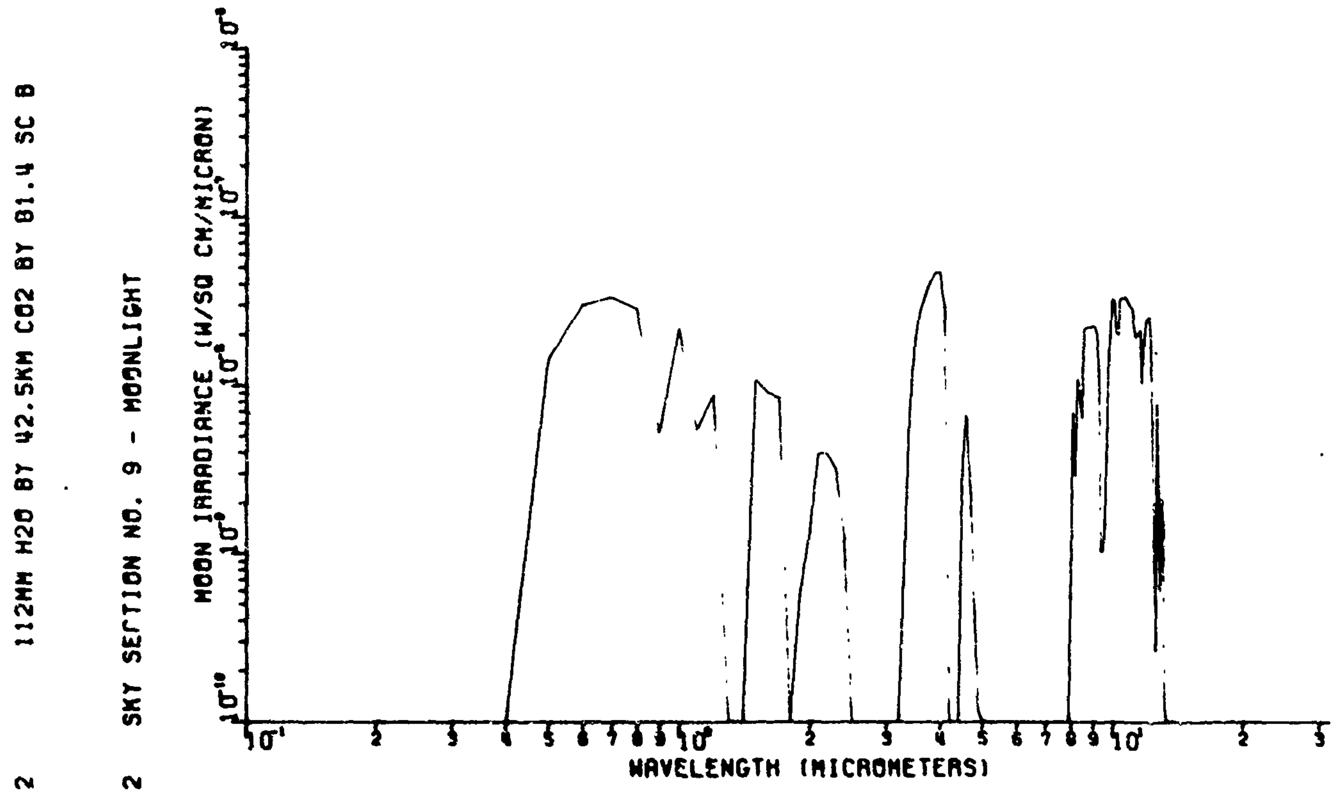


Figure 191. Full Moon Irradiance When Moon is at a Zenith Angle of 81.4°

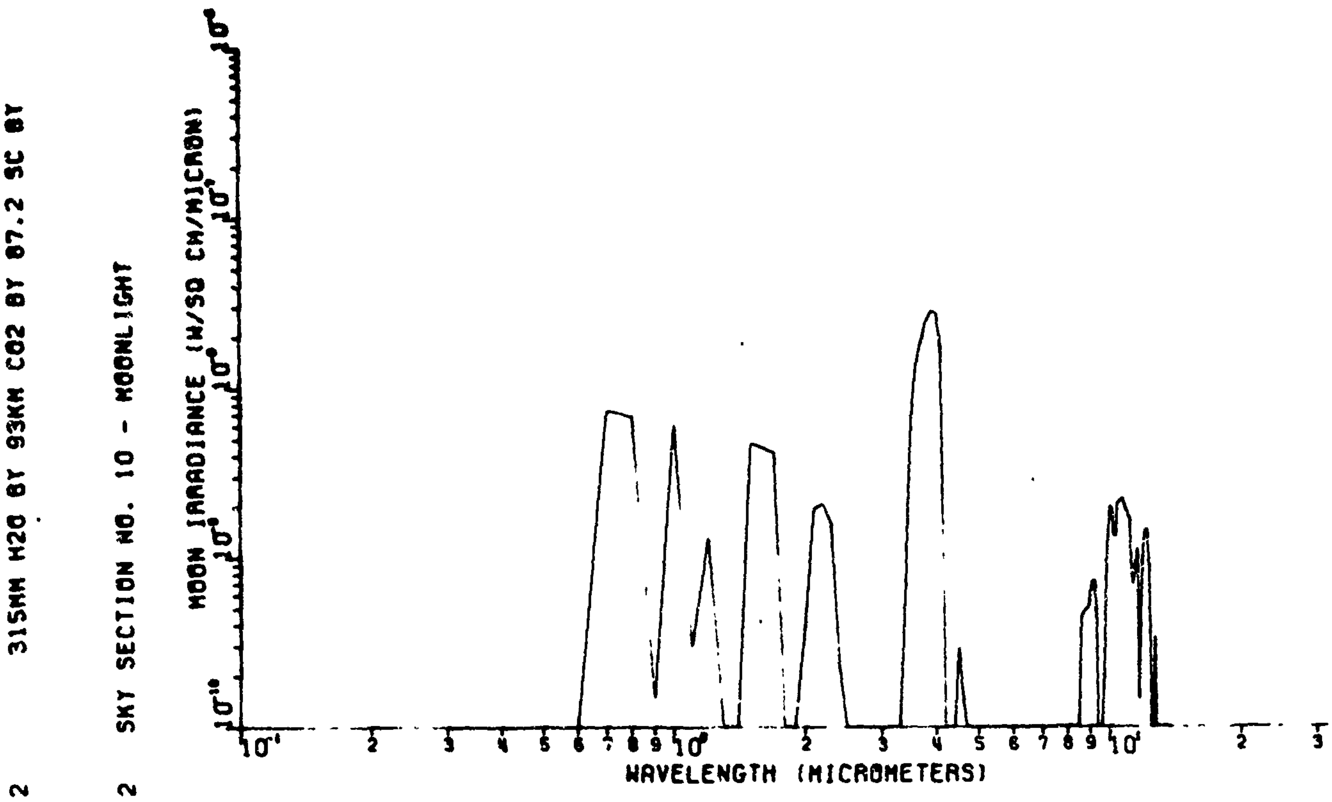


Figure 192. Full Moon Irradiance When Moon is at a Zenith Angle of 87.2°

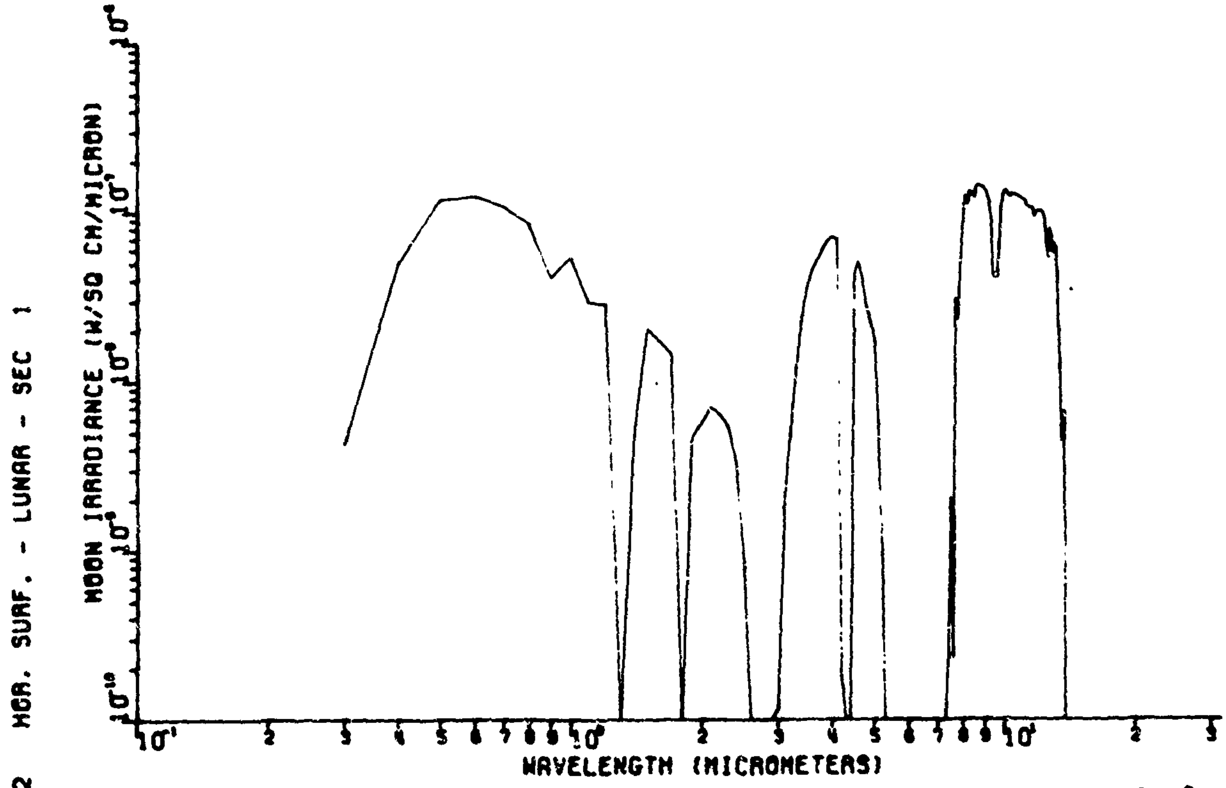


Figure 193. Full Moon Irradiance When Moon is at a Zenith Angle of 18.1°, on a Horizontal Surface

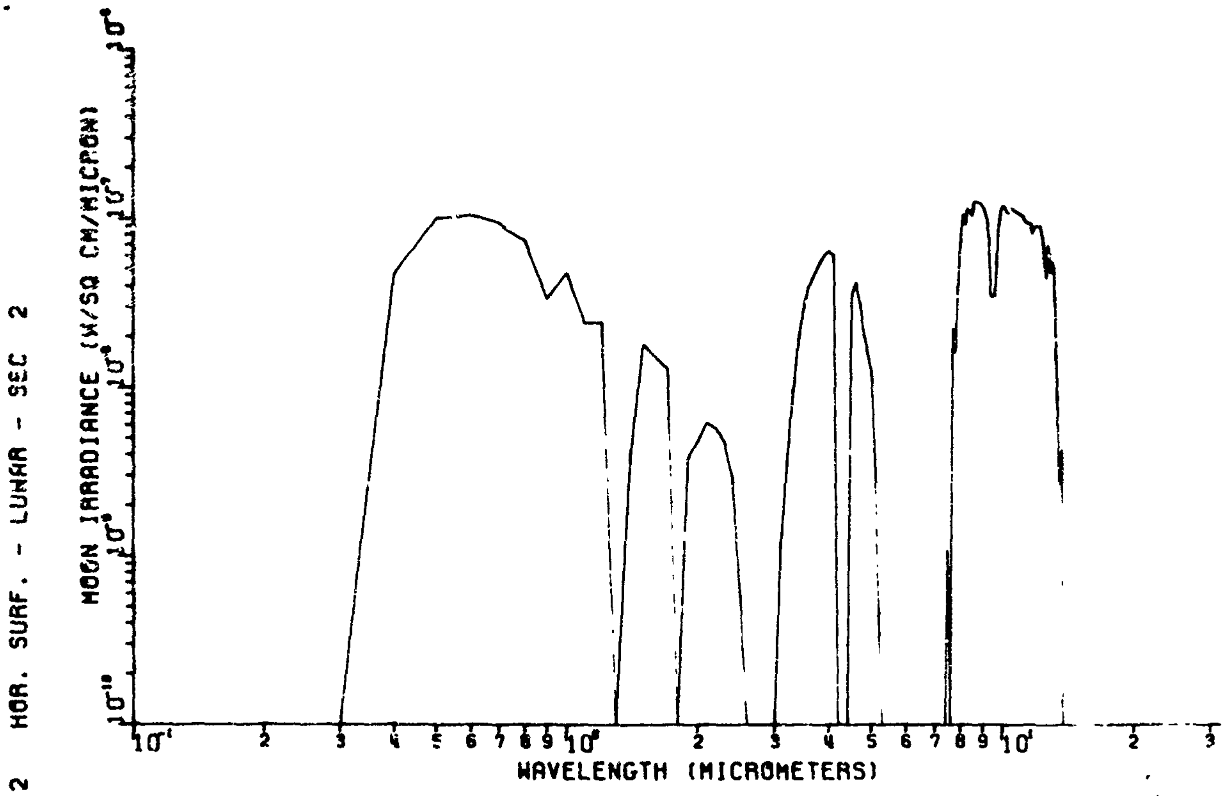


Figure 194. Full Moon Irradiance When Moon is at a Zenith Angle of 31.7°, on a Horizontal Surface

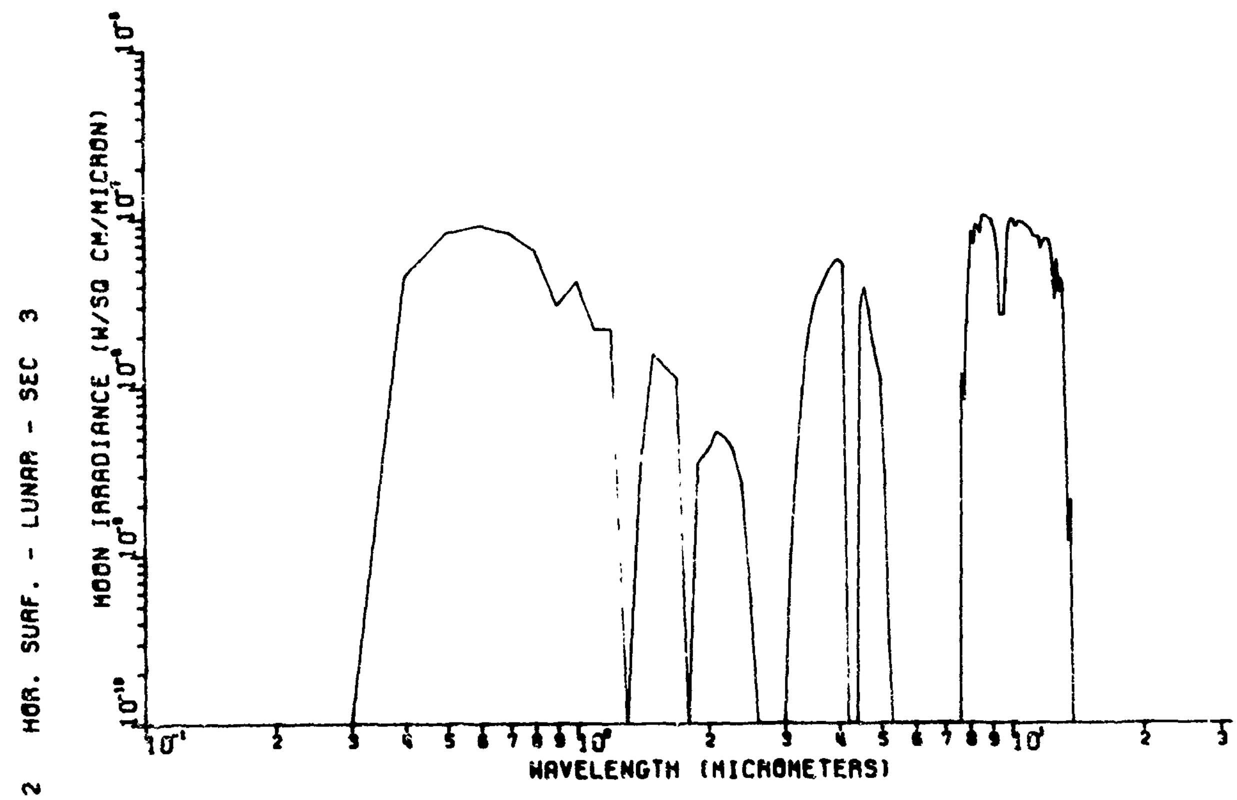


Figure 195. Full Moon Irradiance When Moon is at a Zenith Angle of 41.4°, on a Horizontal Surface

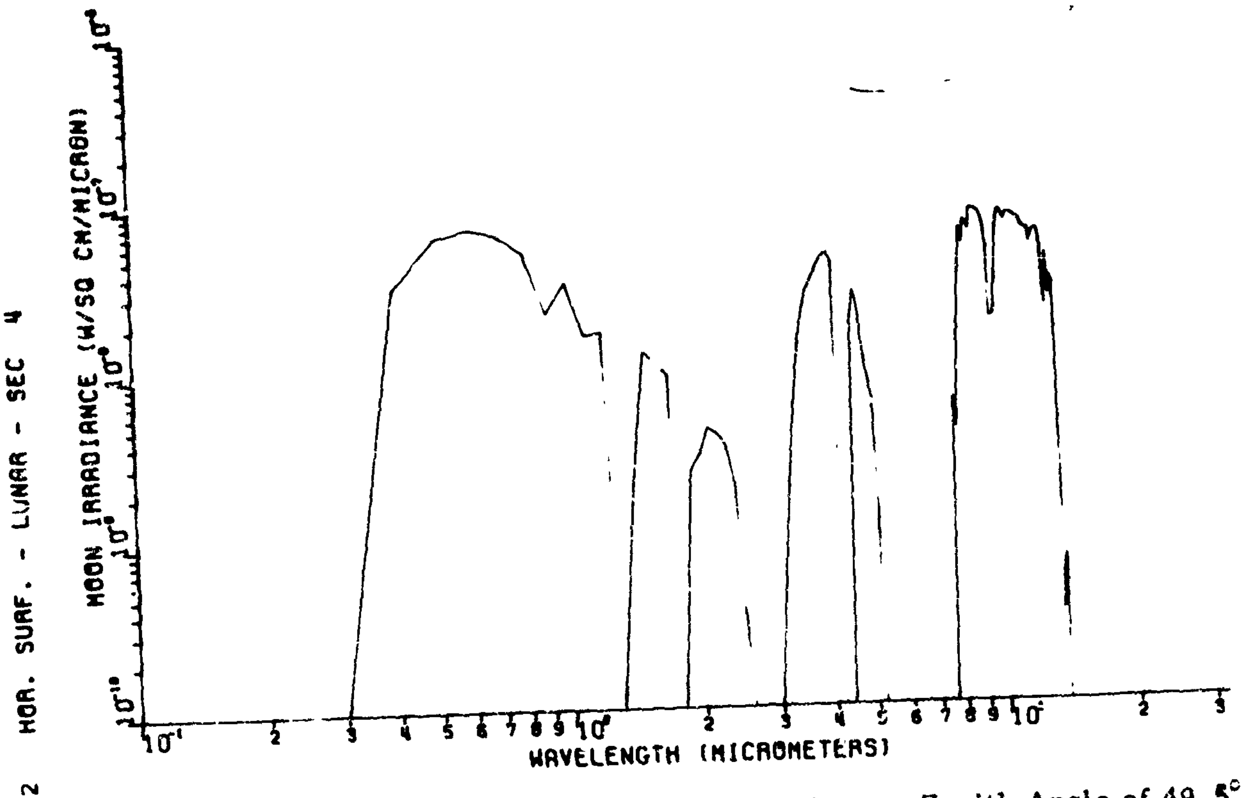


Figure 196. Full Moon Irradiance When Moon is at a Zenith Angle of 49.5°, on a Horizontal Surface

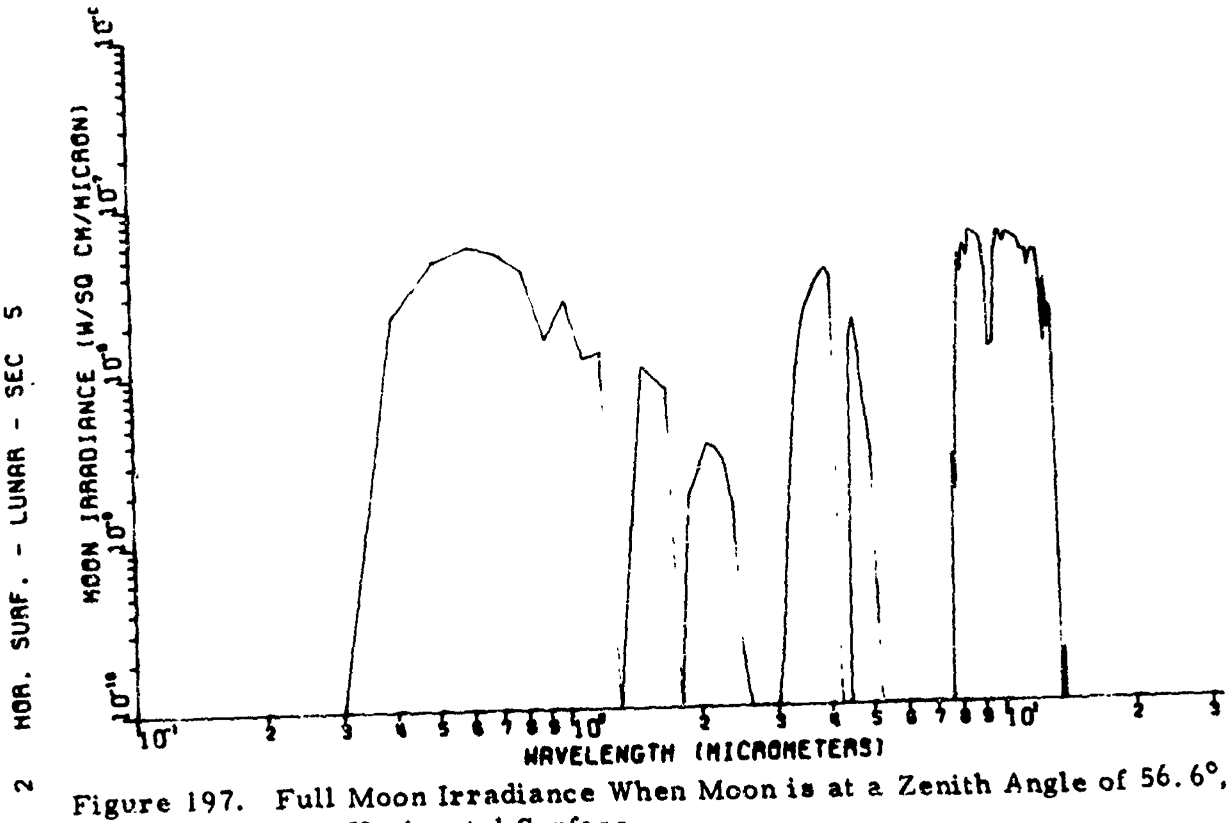


Figure 197. Full Moon Irradiance When Moon is at a Zenith Angle of 56.6°, on a Horizontal Surface

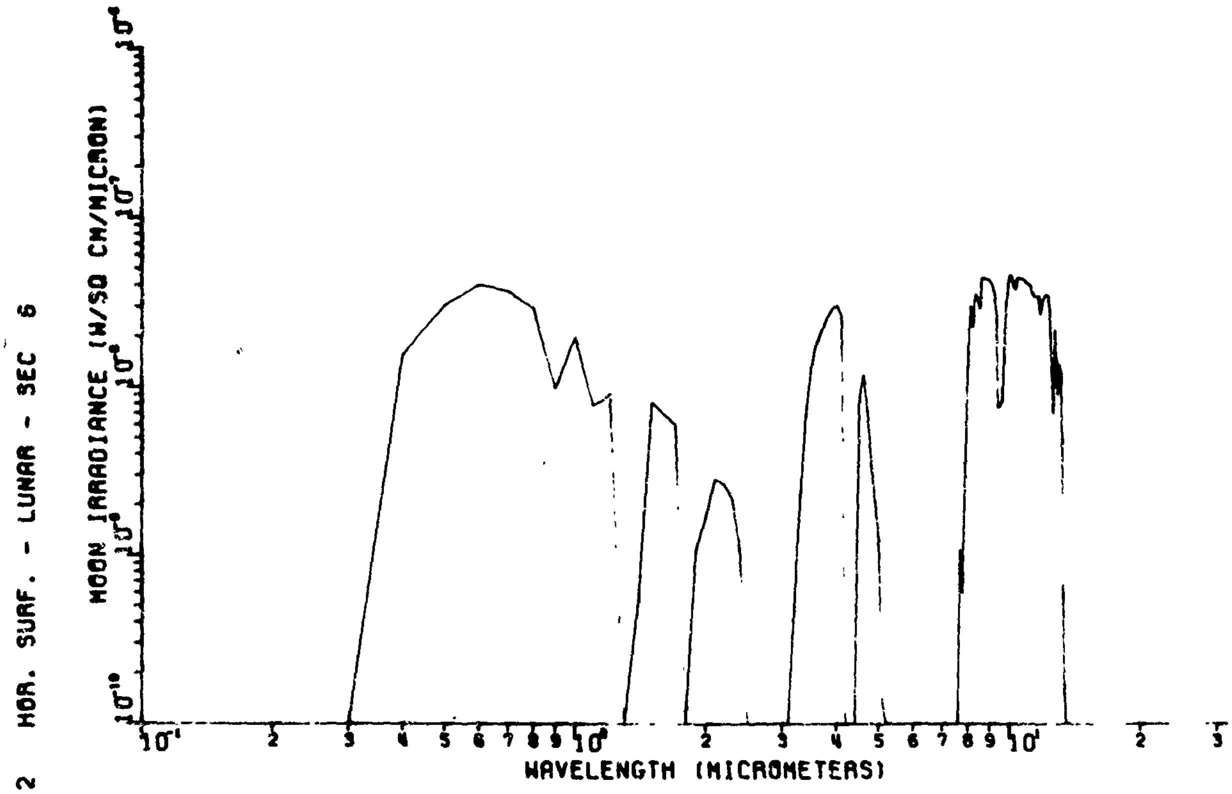


Figure 198. Full Moon Irradiance When Moon is at a Zenith Angle of 63.2°, on a Horizontal Surface

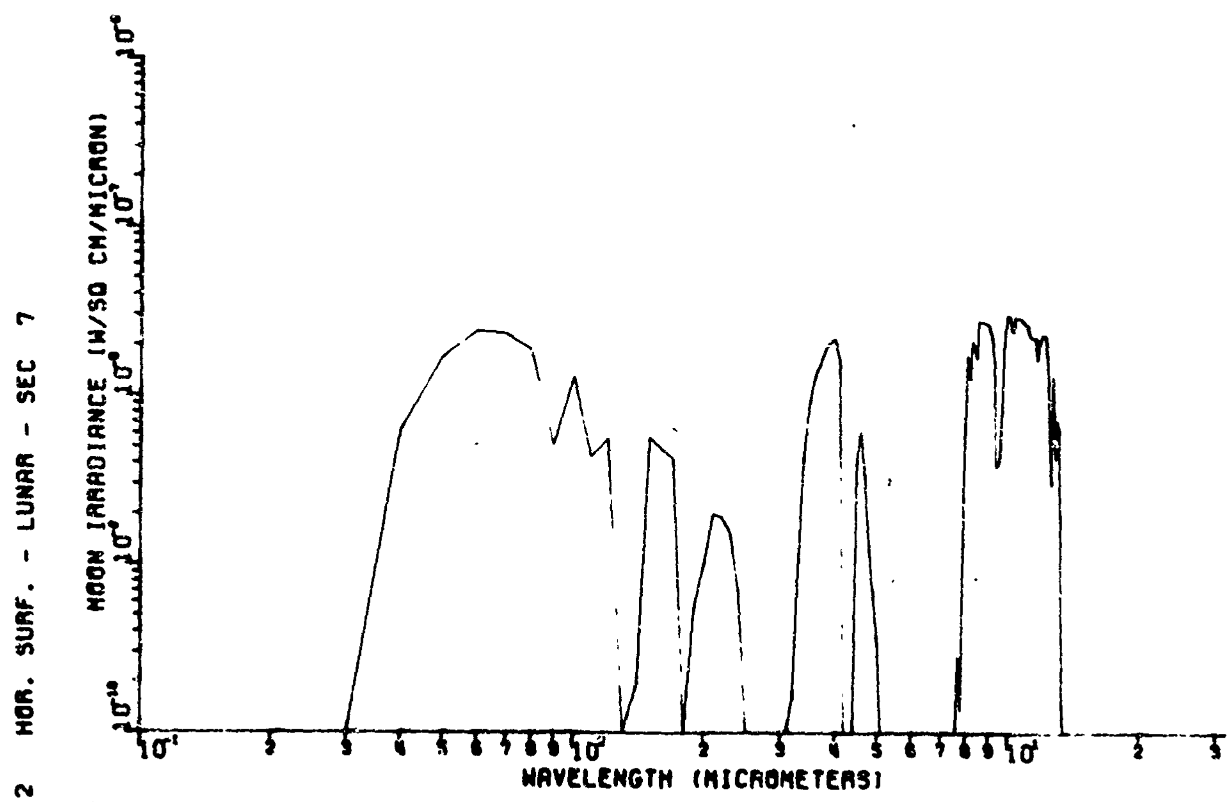


Figure 199. Full Moon Irradiance When Moon is at a Zenith Angle of 69.5°, on a Horizontal Surface

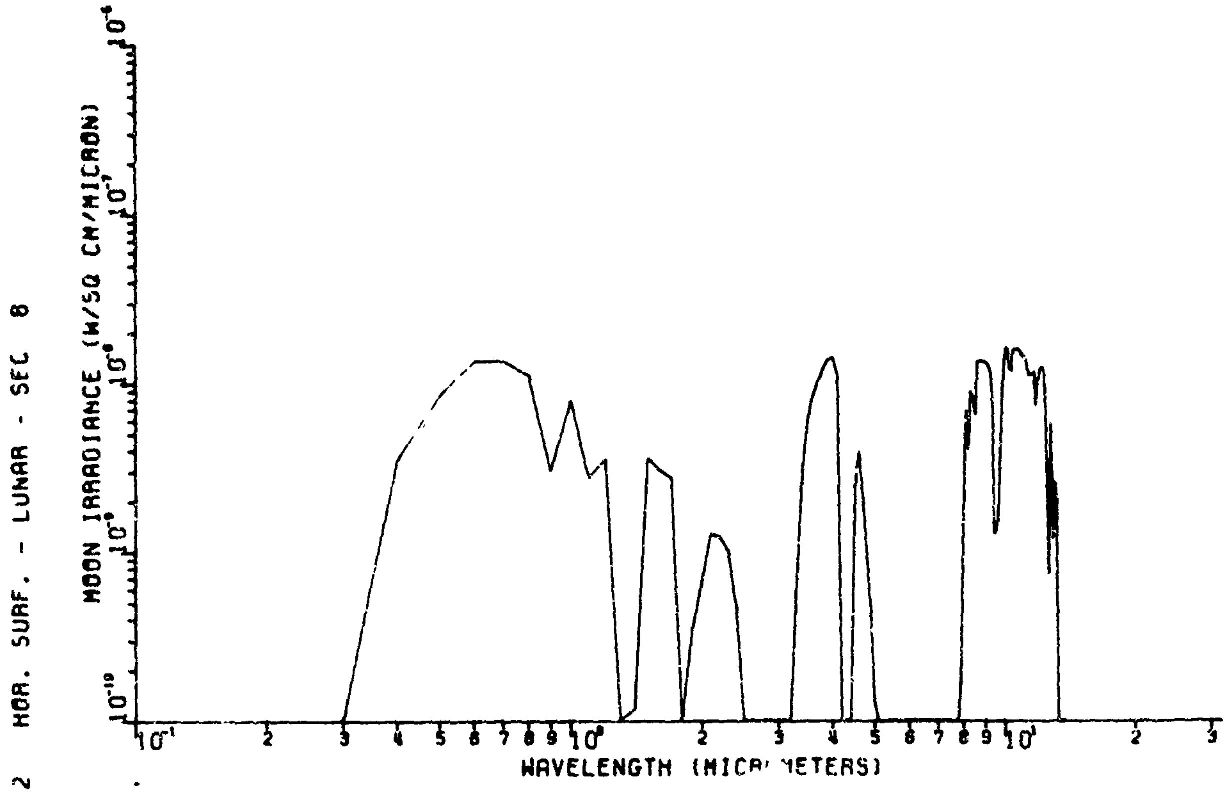


Figure 200. Full Moon Irradiance When Moon is at a Zenith Angle of 75.5°, on a Horizontal Surface

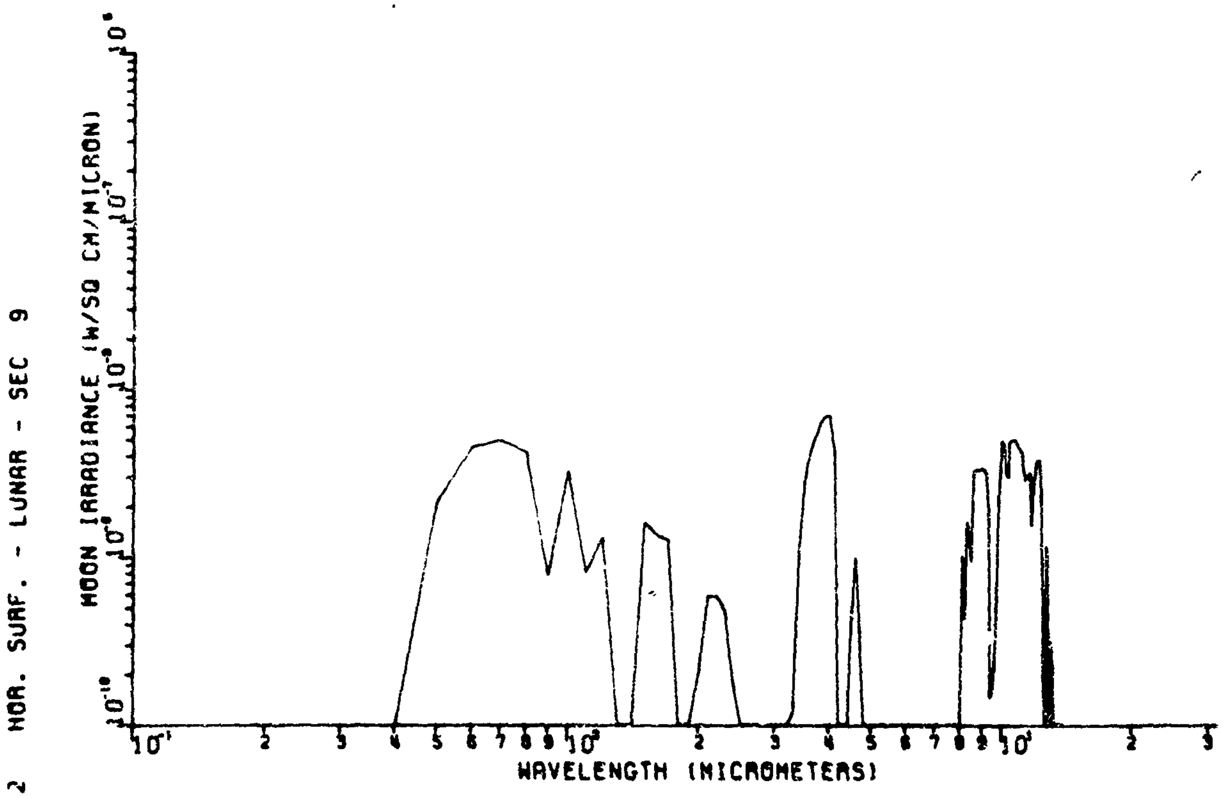


Figure 201. Full Moon Irradiance When Moon is at a Zenith Angle of 81.4°, on a Horizontal Surface

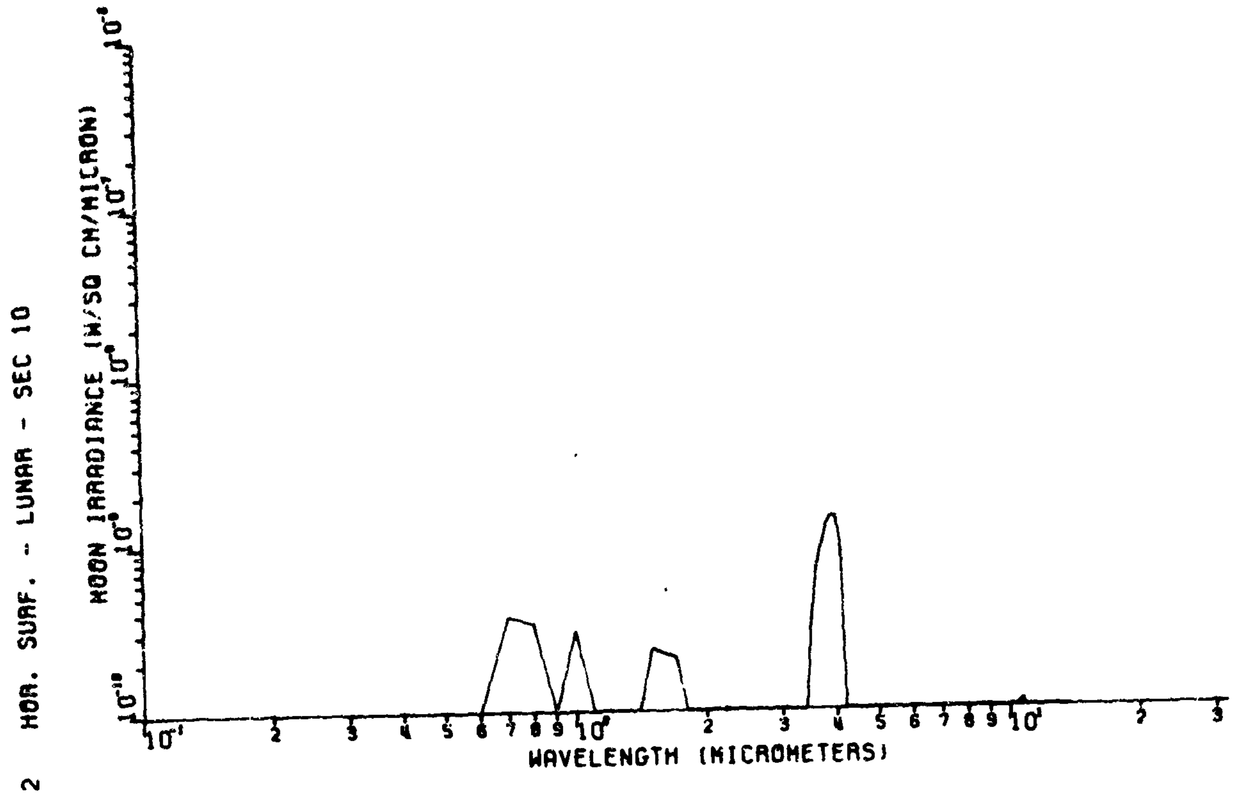


Figure 202. Full Moon Irradiance When Moon is at a Zenith Angle of 87.2° on a Horizontal Surface

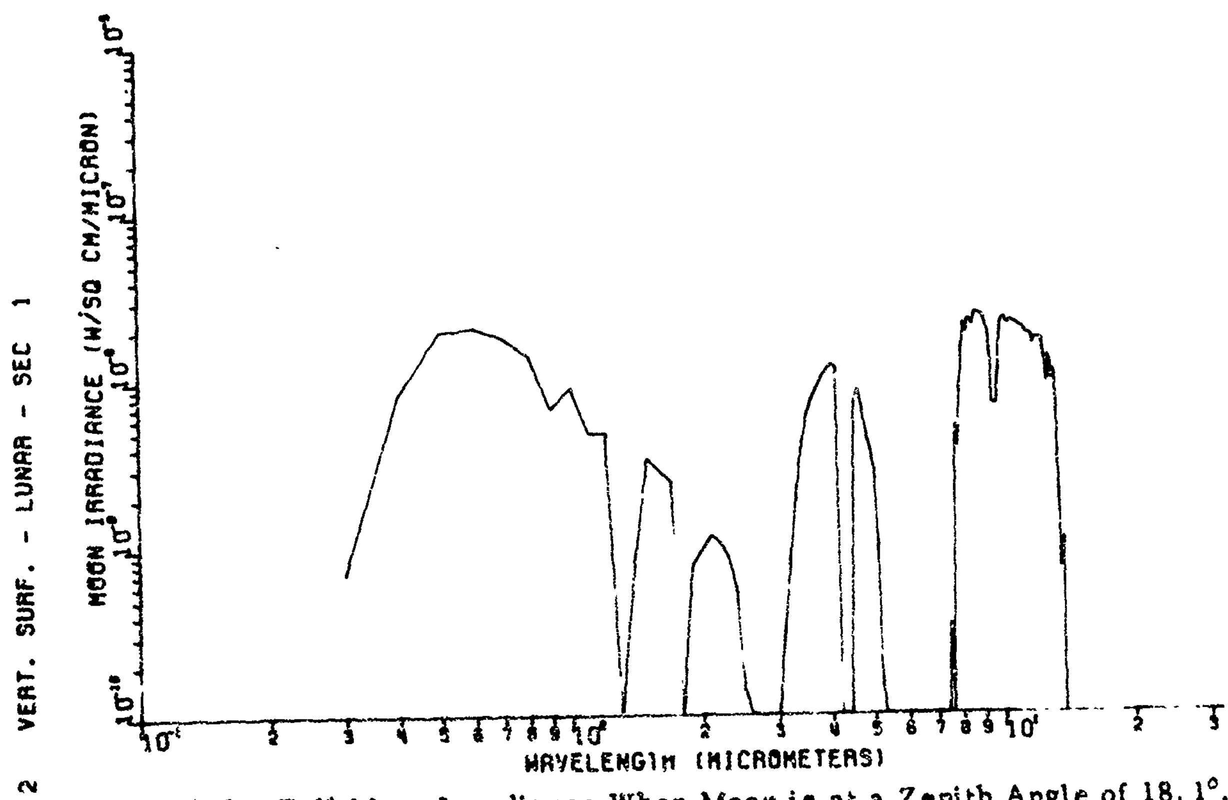


Figure 203. Full Moon Irradiance When Moon is at a Zenith Angle of 18.1°, on a Vertical Surface

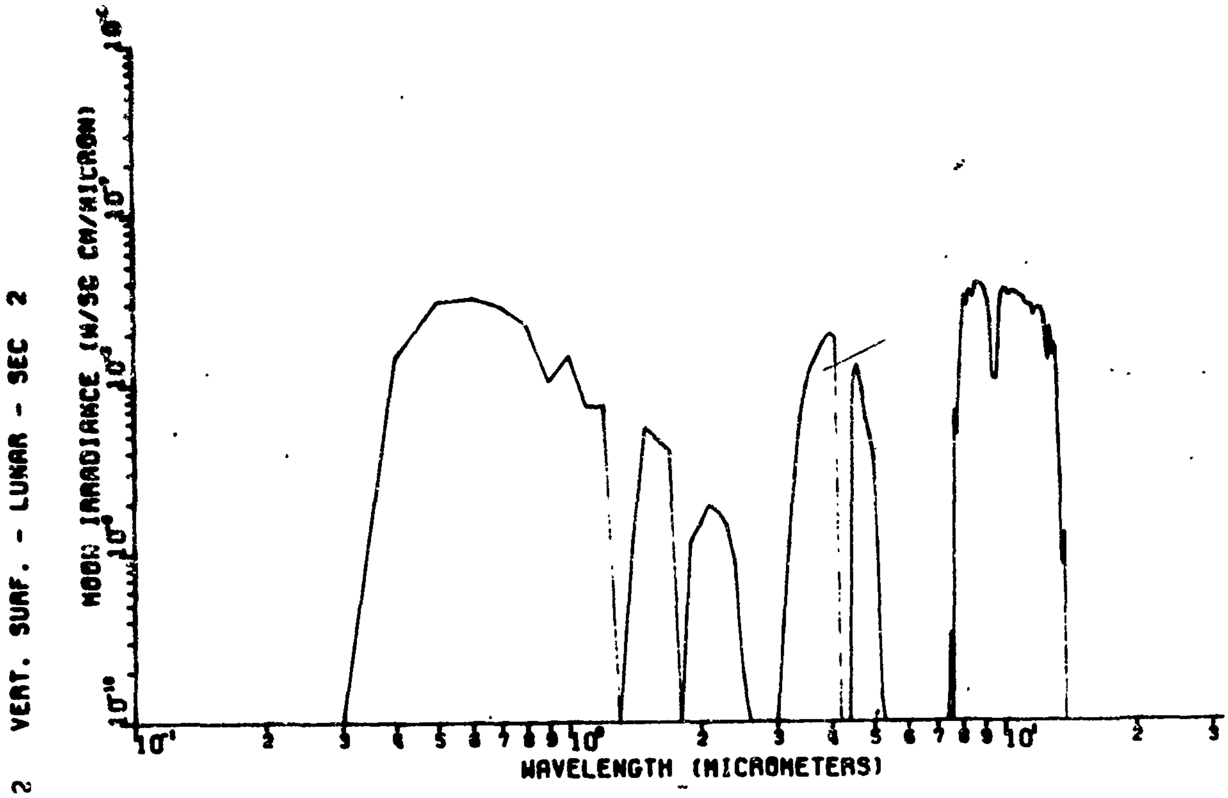


Figure 204. Full Moon Irradiance When Moon is at a Zenith Angle of 31.7°, on a Vertical Surface

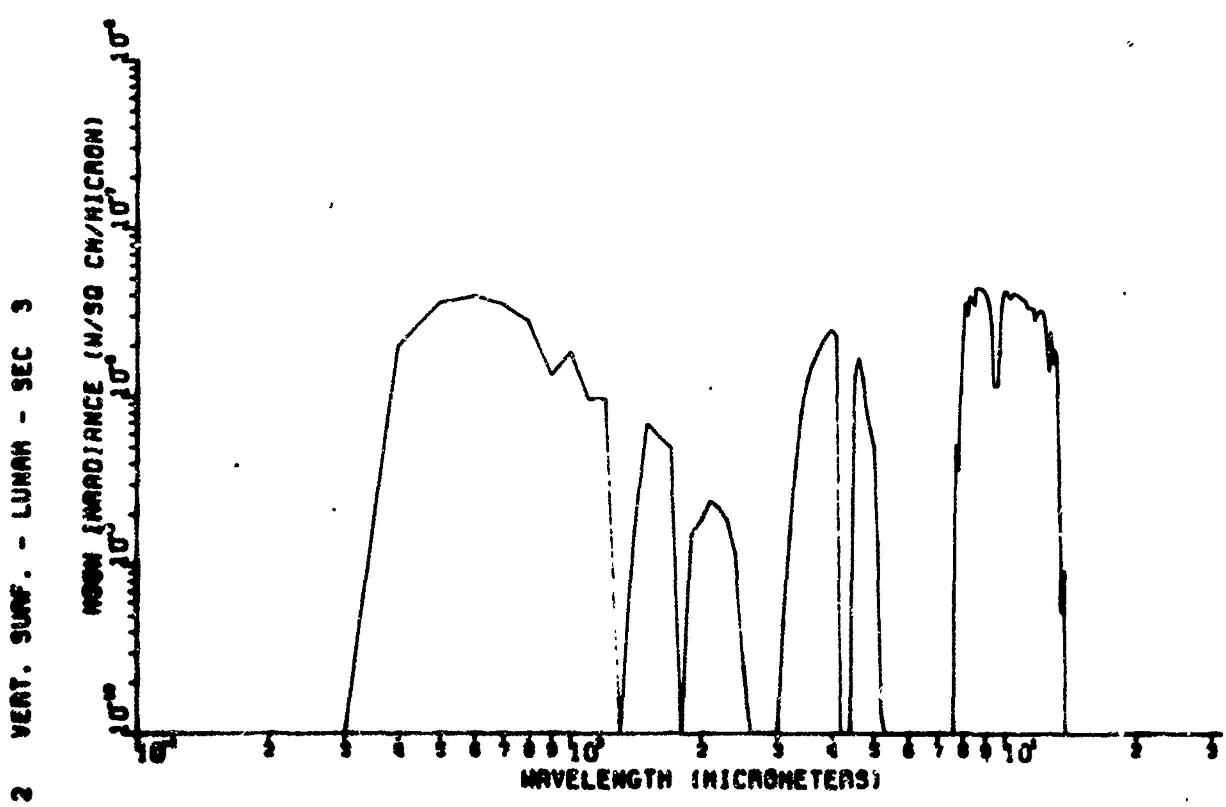


Figure 205. Full Moon Irradiance When Moon is at a Zenith Angle of 41.4°, on a Vertical Surface

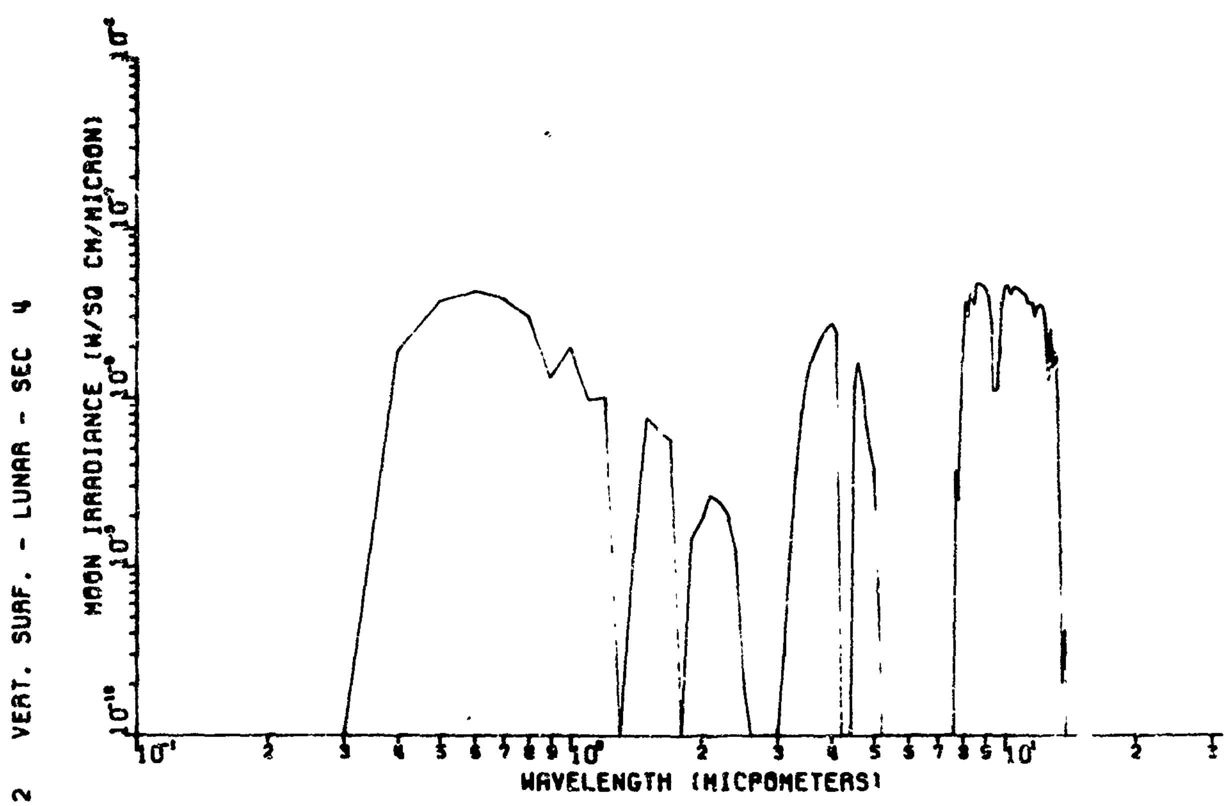


Figure 206. Full Moon Irradiance When Moon is at a Zenith Angle of 49.5°, on a Vertical Surface

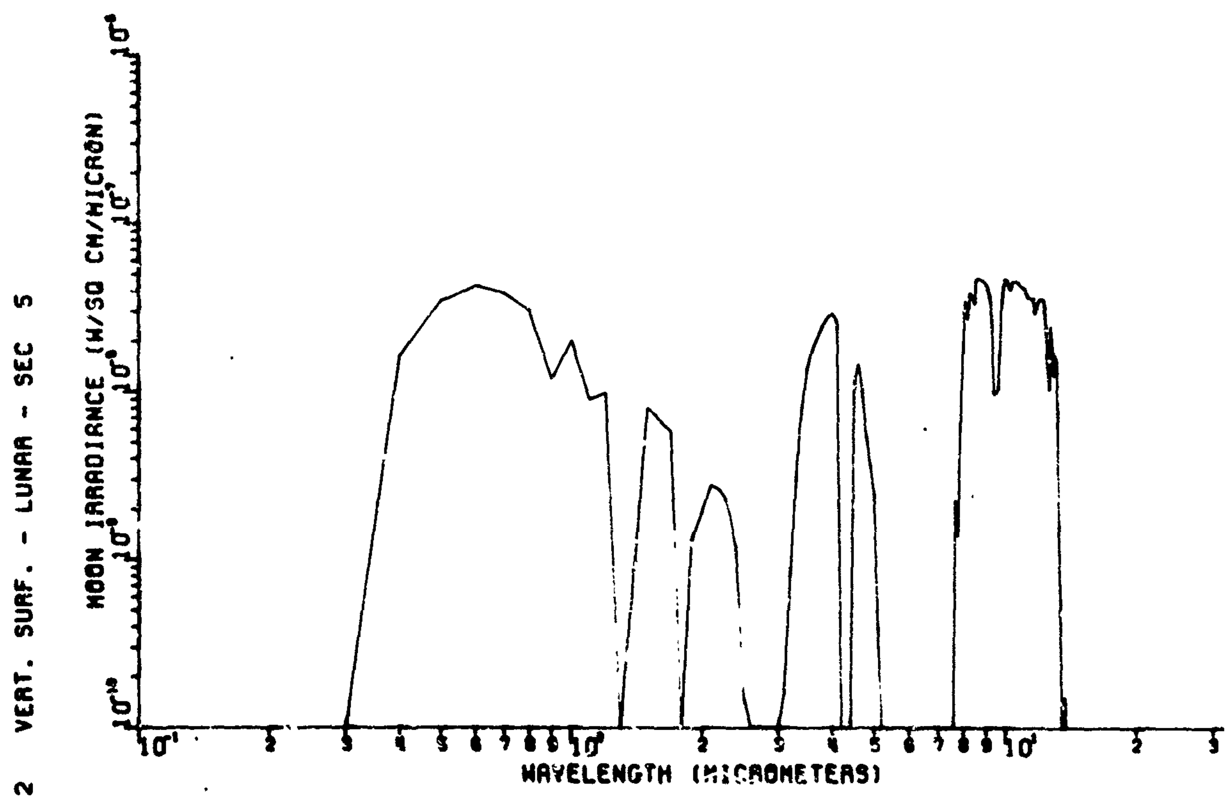


Figure 207. Full Moon Irradiance When Moon is at a Zenith Angle of 56.6°, on a Vertical Surface

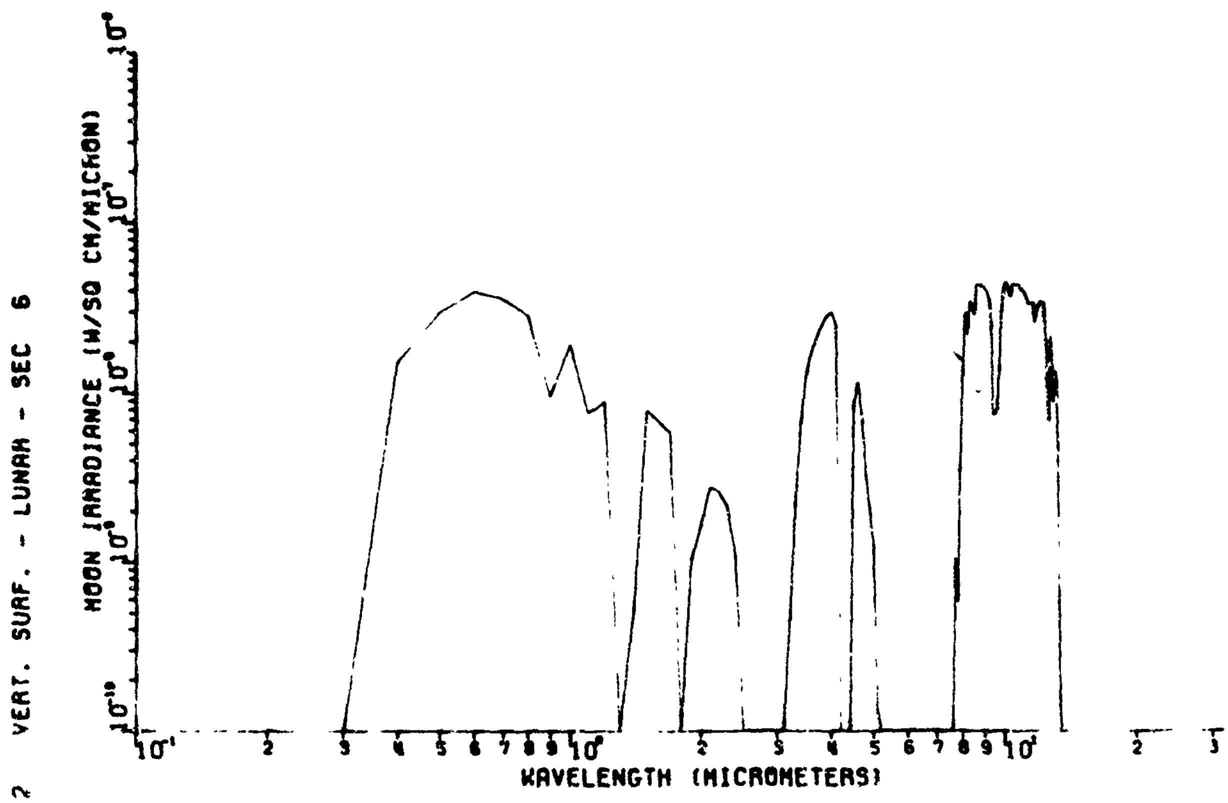


Figure 208. Full Moon Irradiance When Moon is at a Zenith Angle of 63.2°, on a Vertical Surface

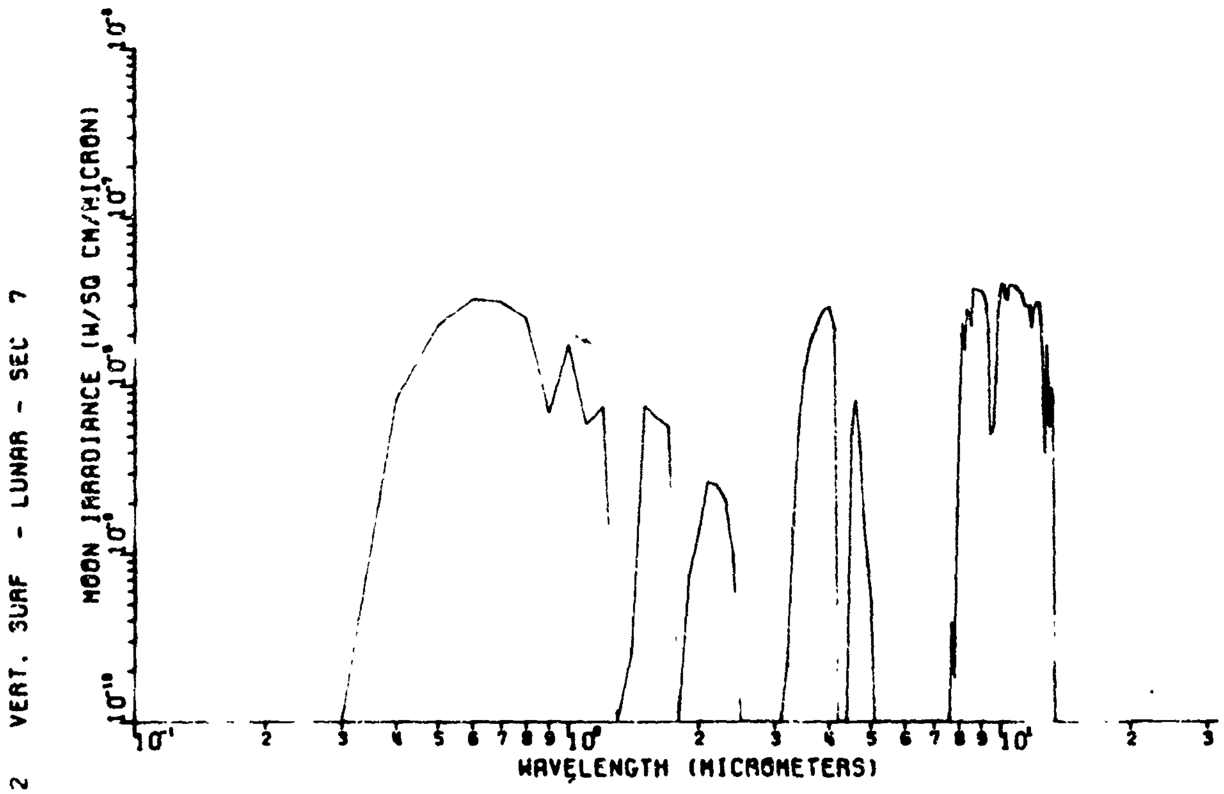


Figure 209. Full Moon Irradiance When Moon is at a Zenith Angle of 69.5°, on a Vertical Surface

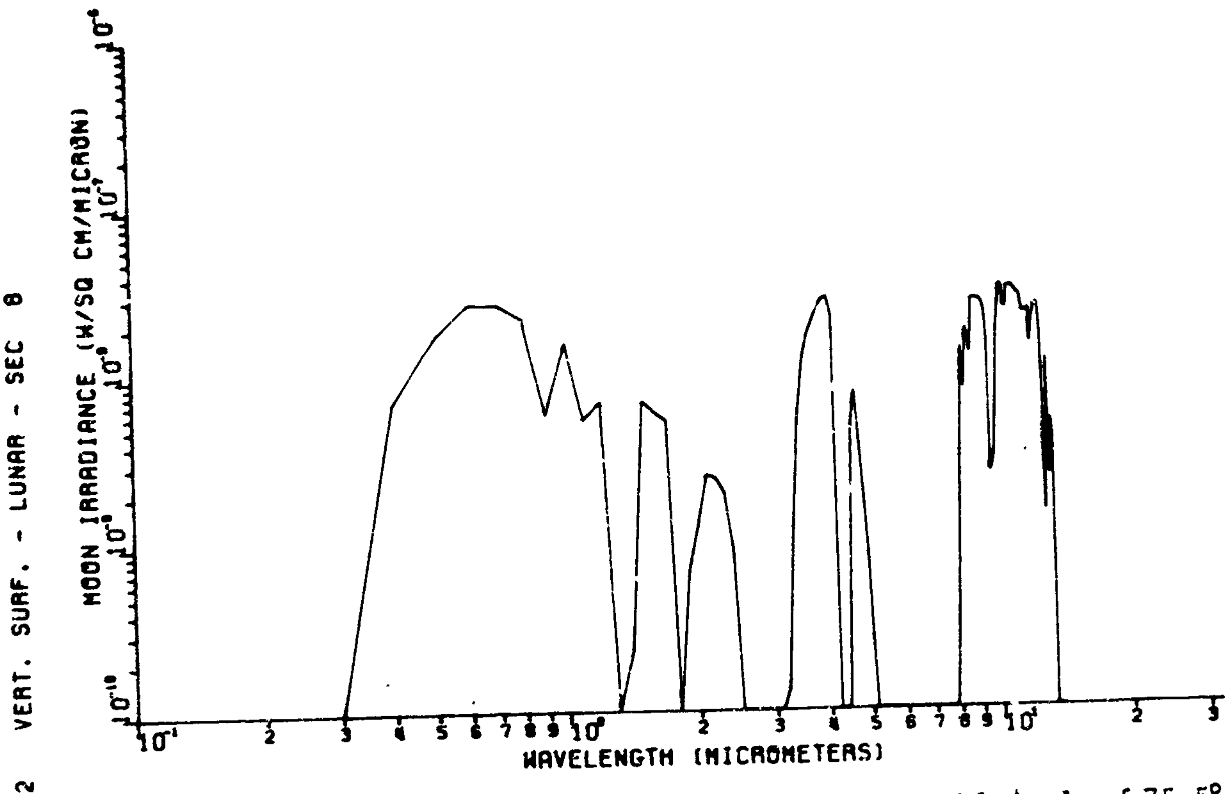


Figure 210. Full Moon Irradiance When Moon is at a Zenith Angle of 75.5°, on a Vertical Surface

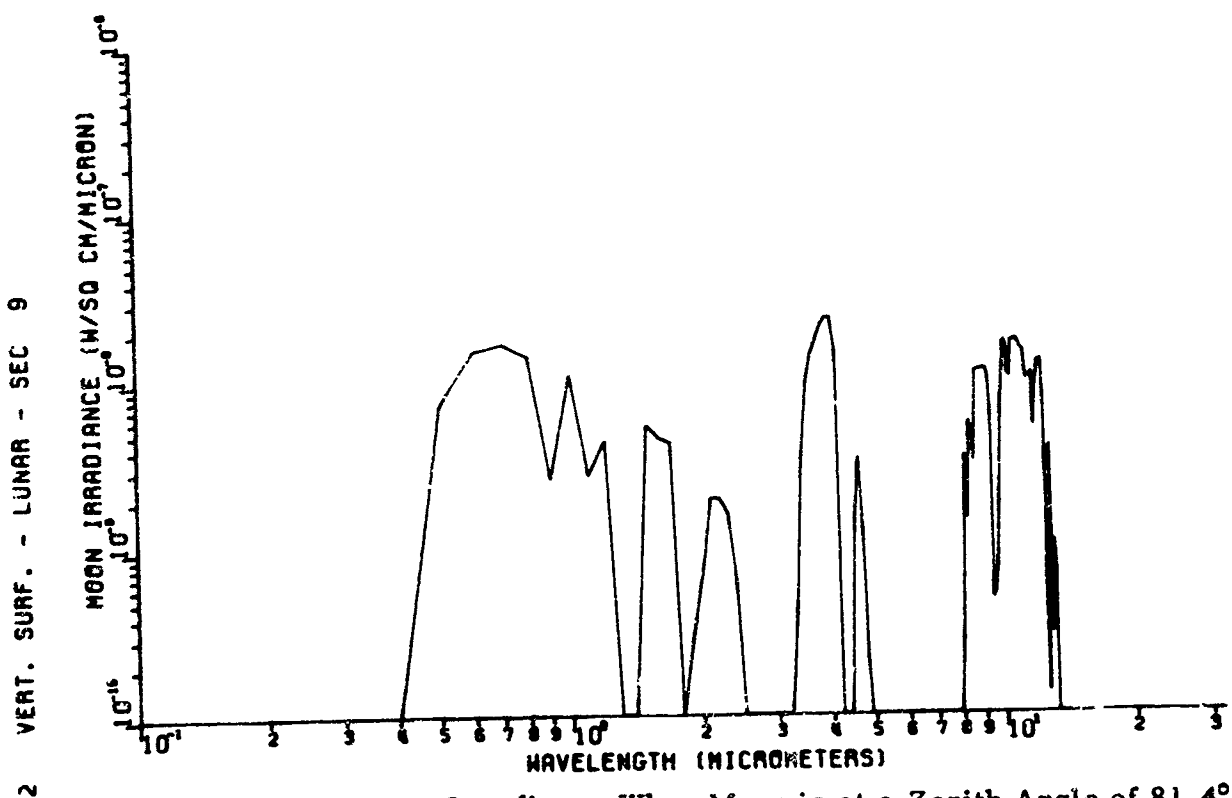


Figure 211. Full Moon Irradiance When Moon is at a Zenith Angle of 81.4°, on a Vertical Surface

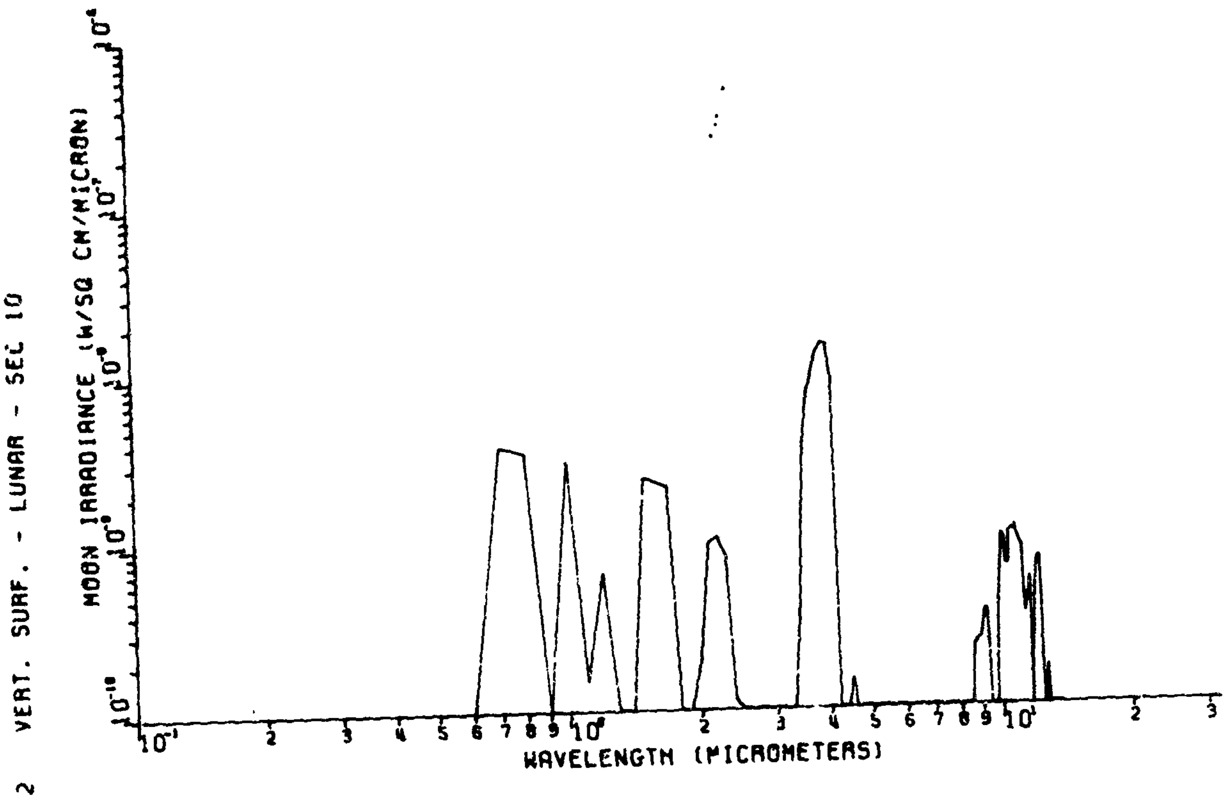


Figure 212. Full Moon Irradiance When Moon is at a Zenith Angle of 87.2°, on a Vertical Surface

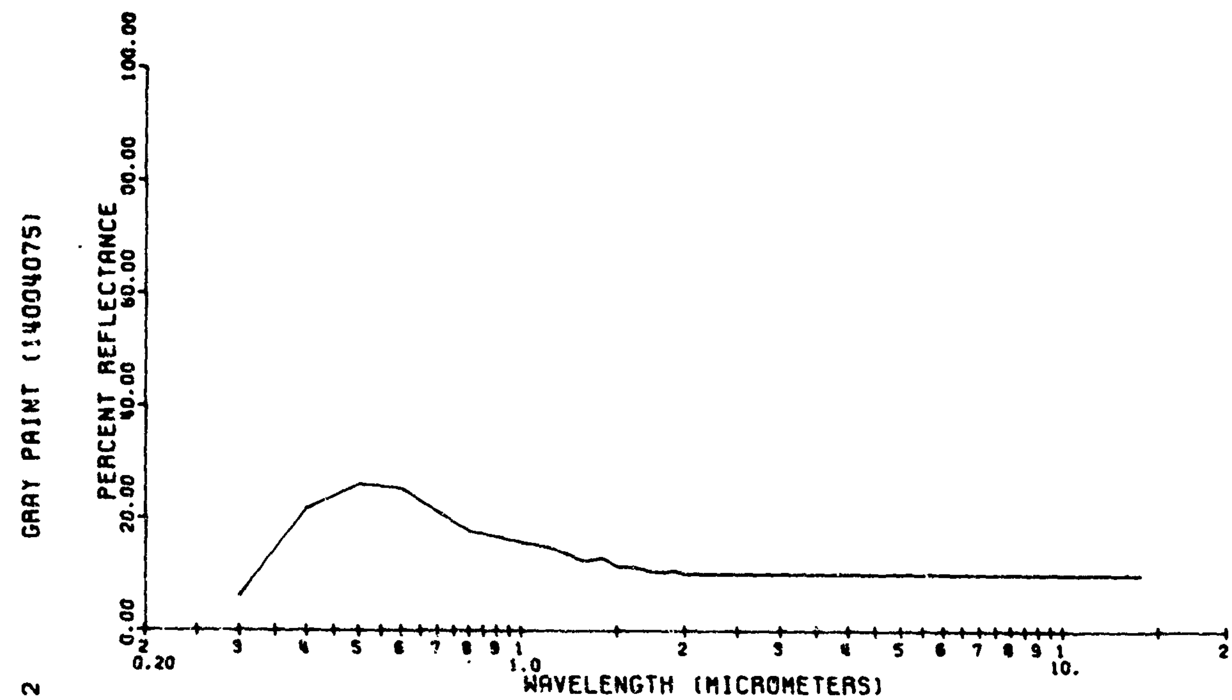


Figure 214. Spectral Reflectance of a Typical Naval Gray Paint

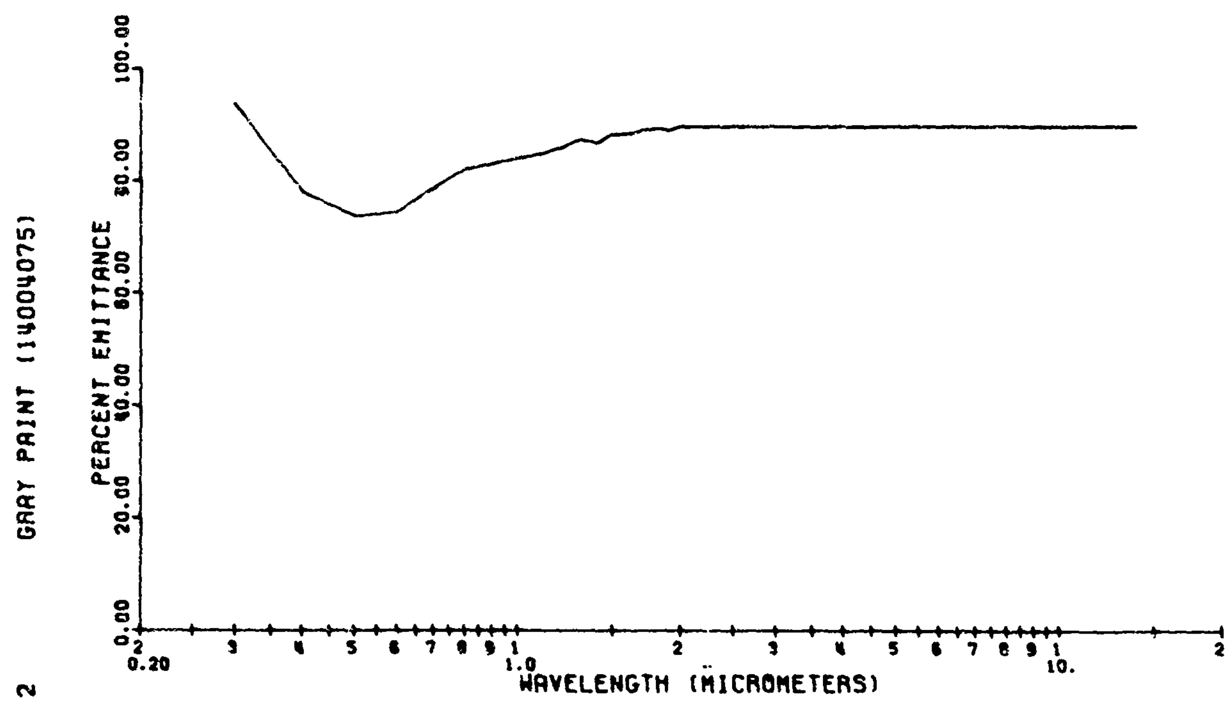


Figure 215. Spectral Emittance of a Typical Naval Gray Paint

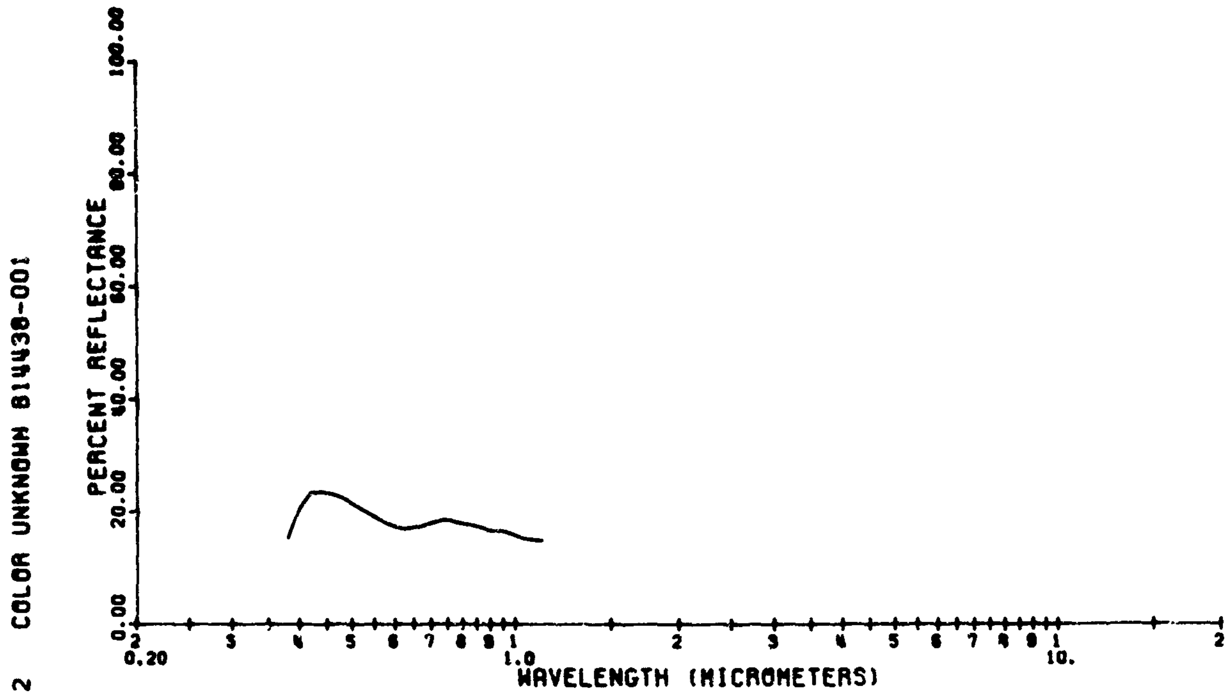


Figure 216. Spectral Reflectance of a Gray Naval Paint from Midship Hull

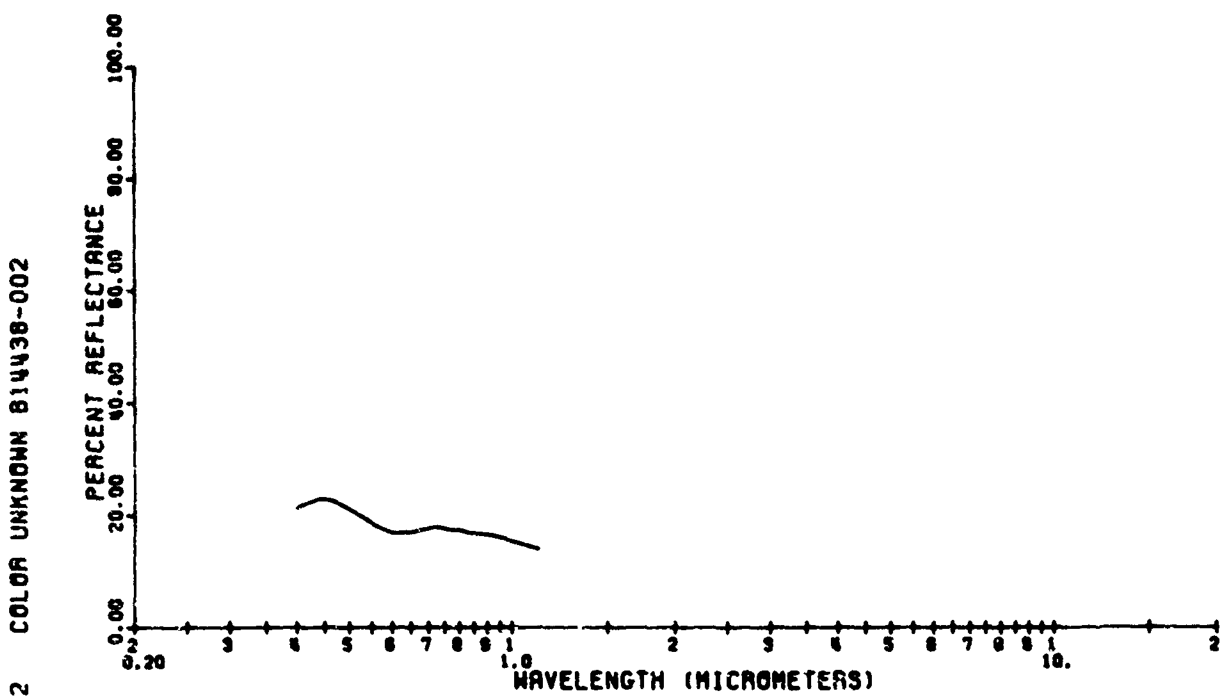


Figure 217. Spectral Reflectance of a Gray Naval Paint from Port Side Hull

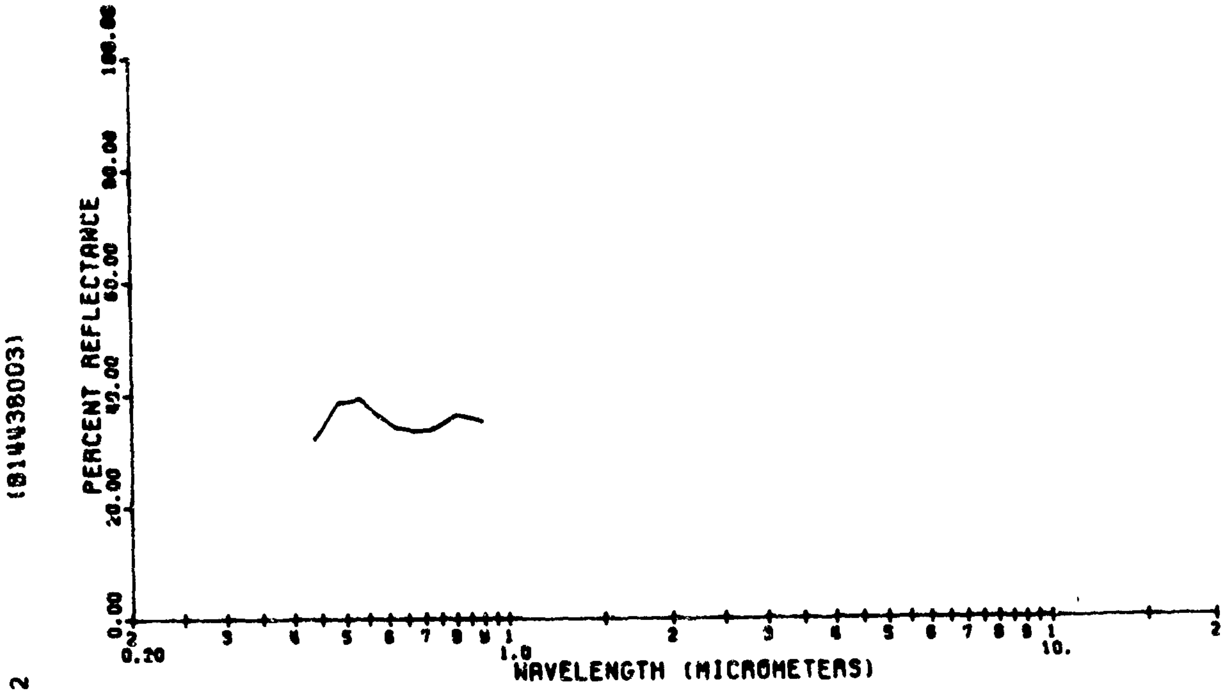


Figure 218. Spectral Reflectance of a Gray Naval Paint from a Patrol Craft

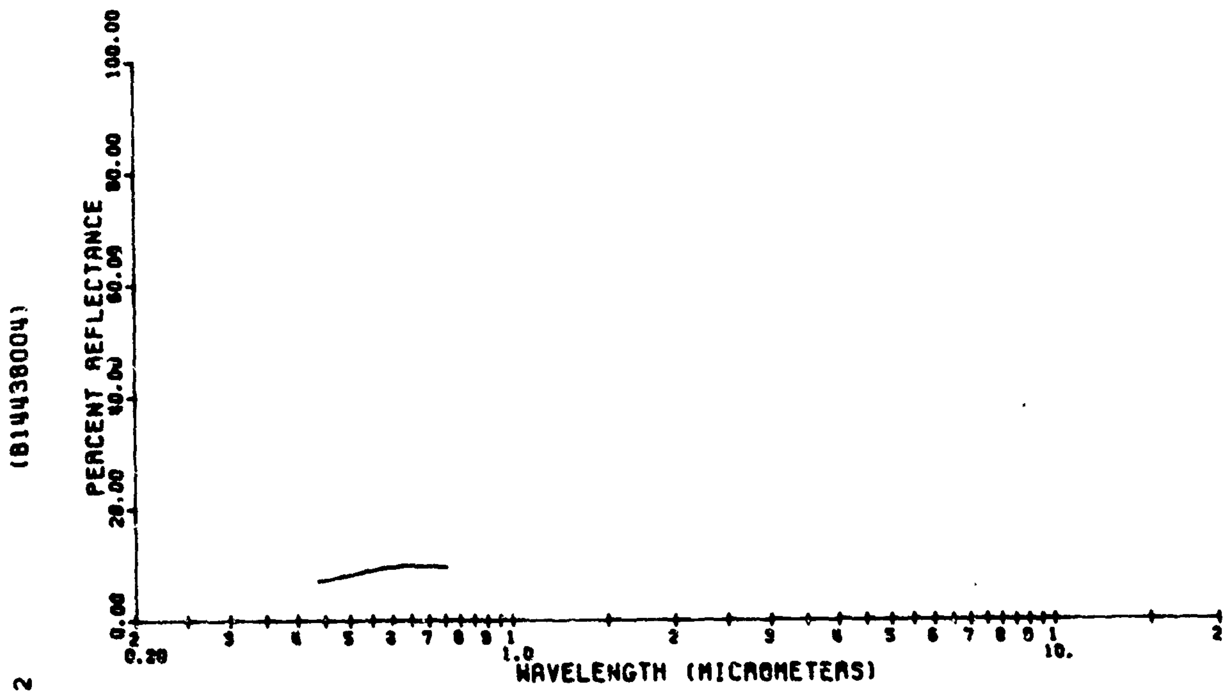


Figure 219. Spectral Reflectance of an Olive Green Naval Paint from a Landing Craft

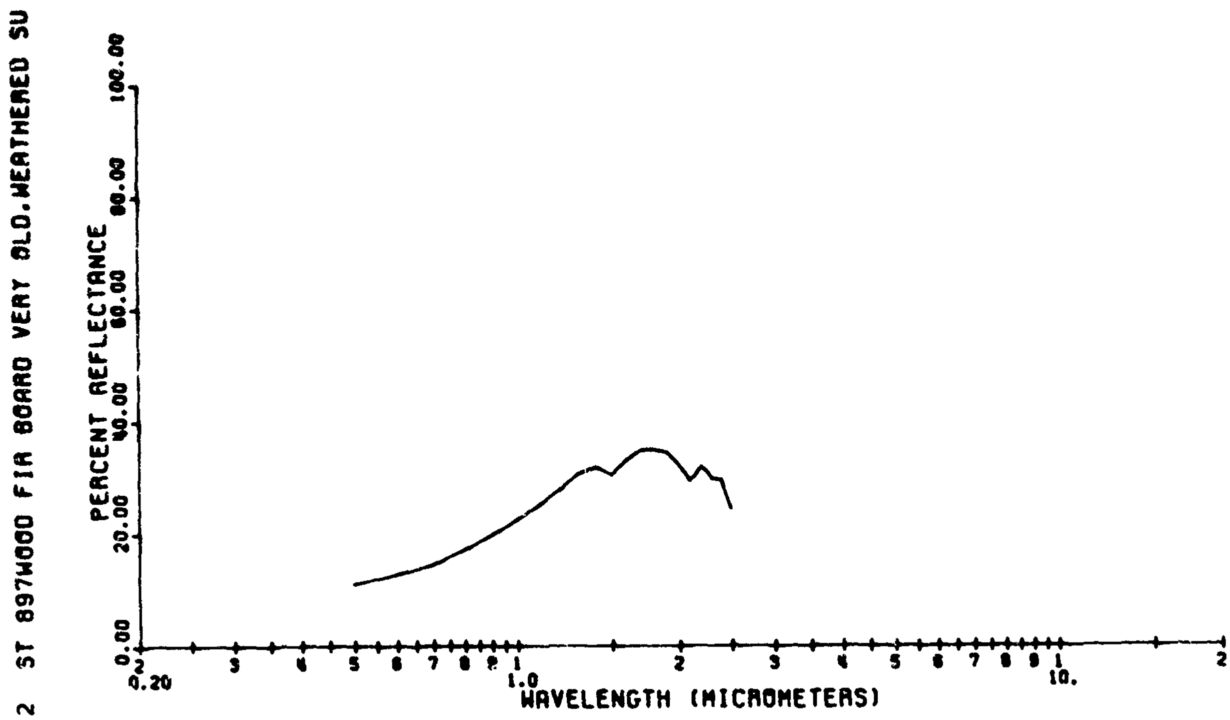


Figure 220. Spectral Reflectance of a Weathered Fir Board

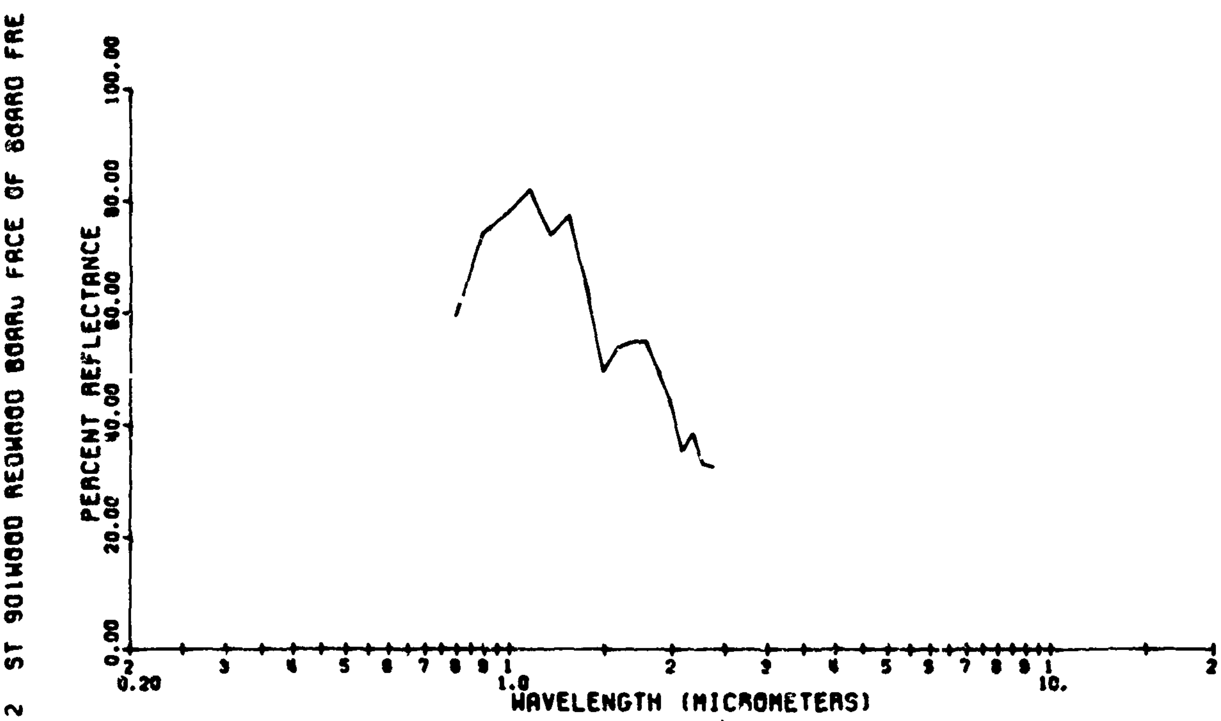


Figure 221. Spectral Reflectance of a Redwood Board

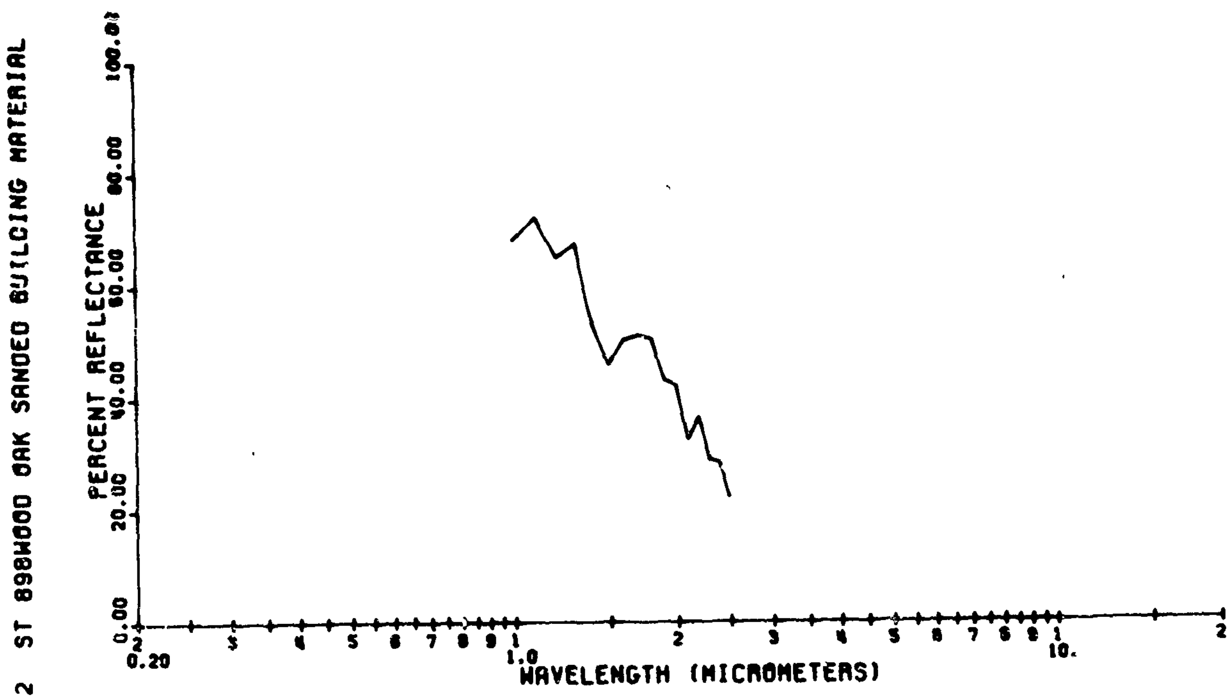


Figure 222. Spectral Reflectance of a Sanded Oak Board

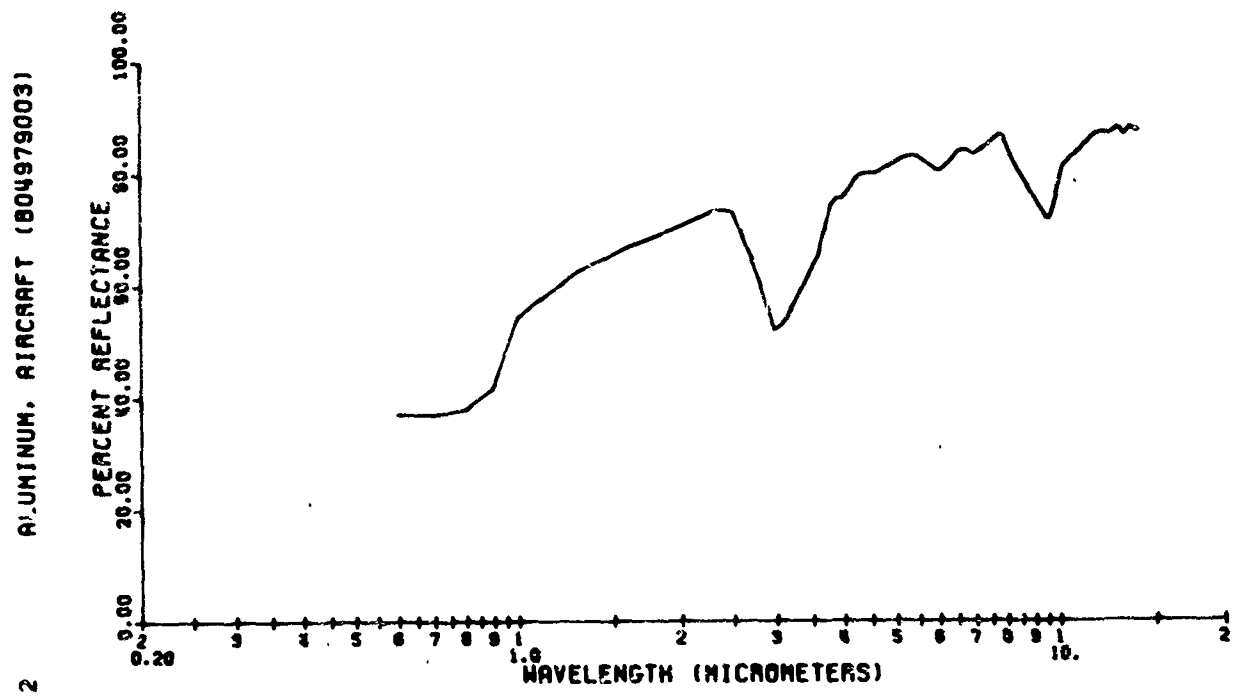


Figure 223. Spectral Reflectance of a Weathered Aircraft Skin

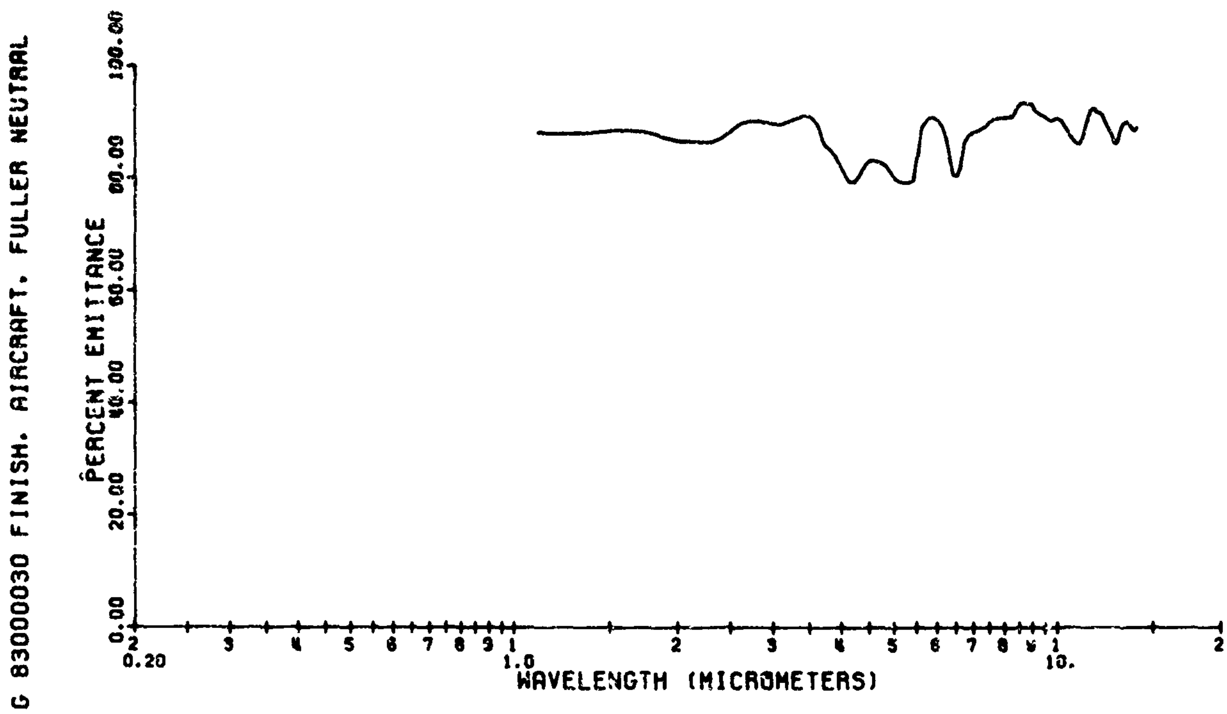


Figure 224. Spectral Emittance of Fuller Neutral Finish on Aircraft Skin

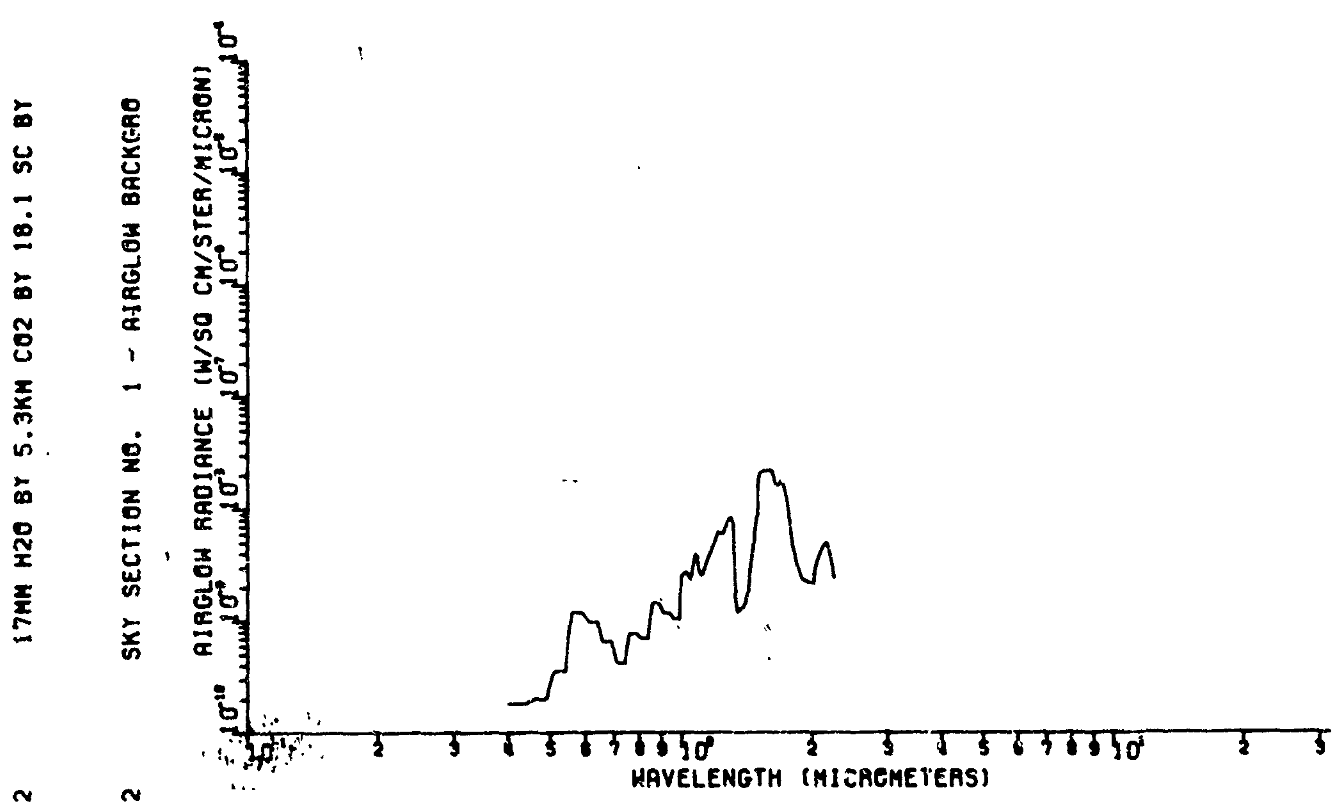


Figure 225. Nightglow as a Background for Sky Segment 1, Zenith Angle of 18.1°

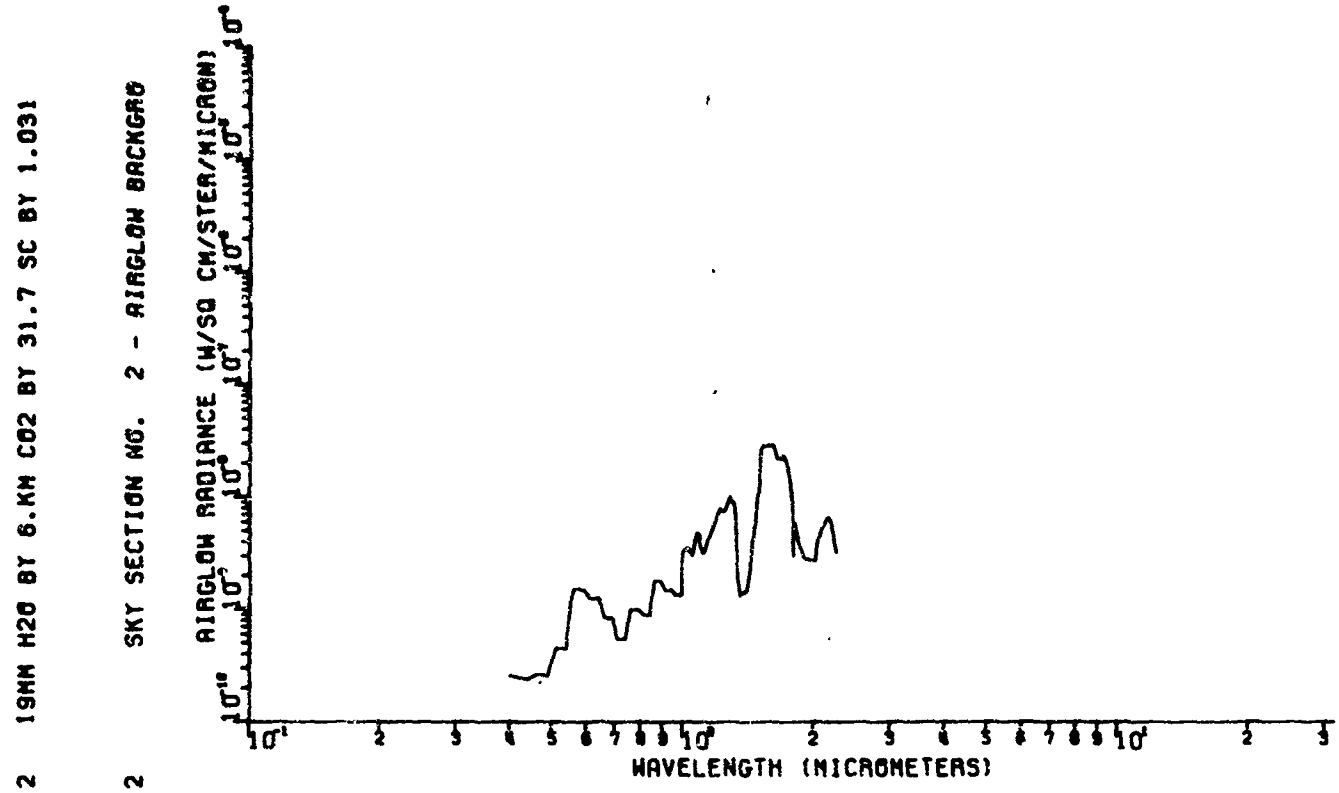


Figure 226. Nightglow as a Background for Sky Segment 2, Zenith Angle of 31.7°

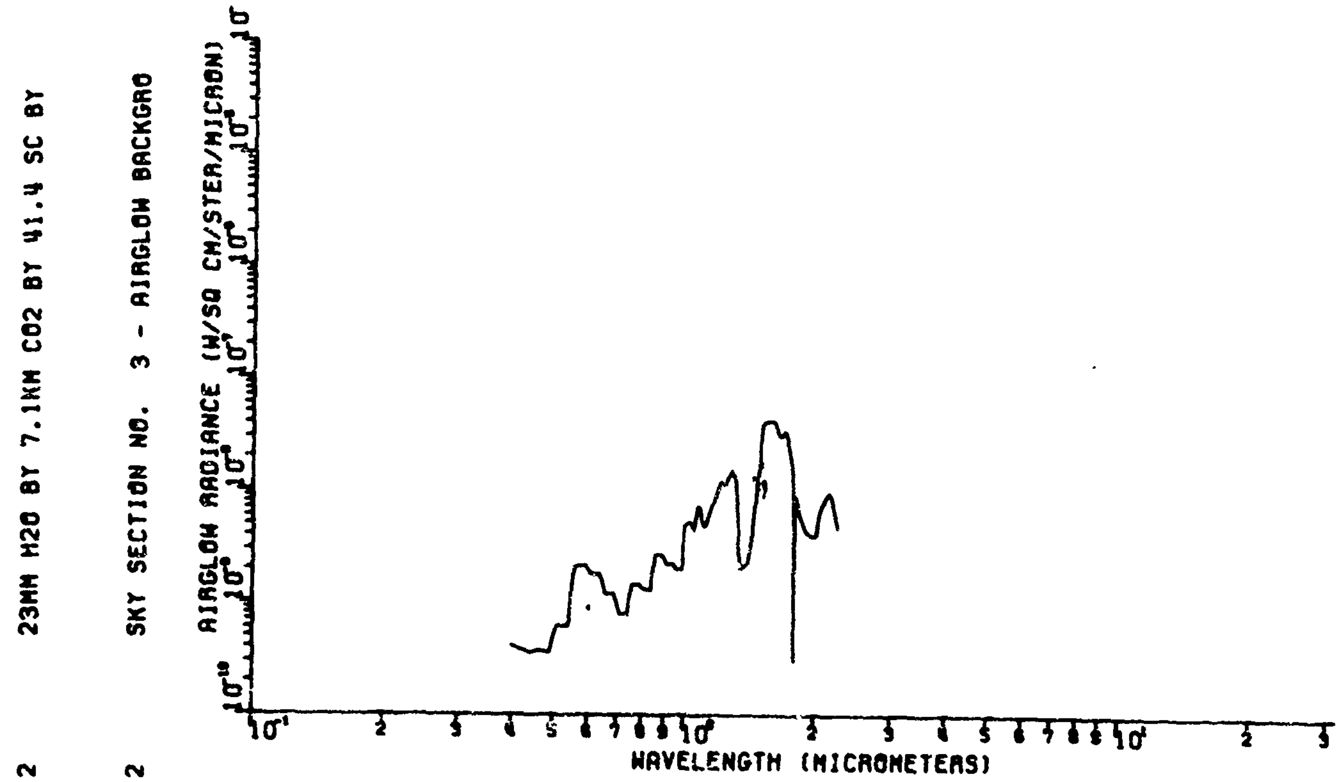


Figure 227. Nightglow as a Background for Sky Segment 3, Zenith Angle of 41.4°

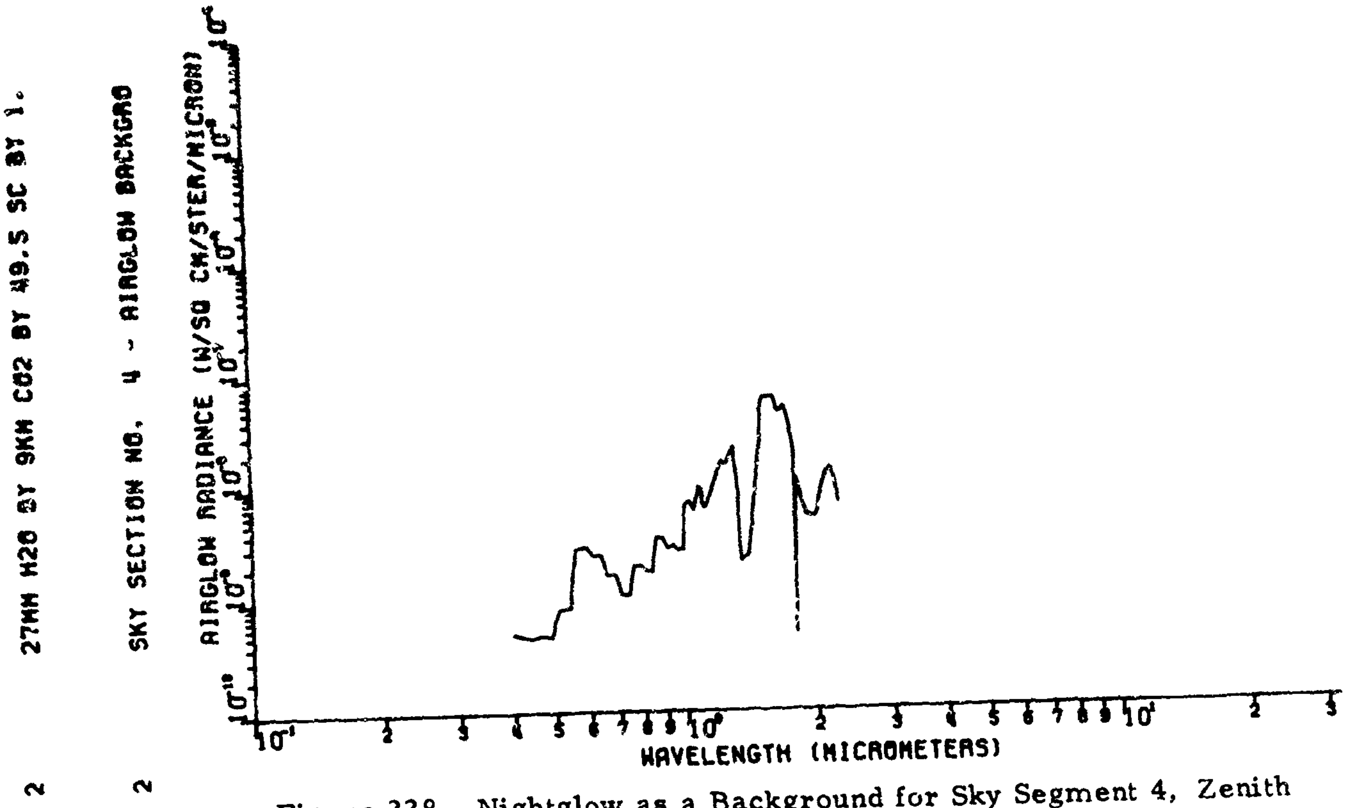


Figure 228. Nightglow as a Background for Sky Segment 4, Zenith Angle of 49.5°

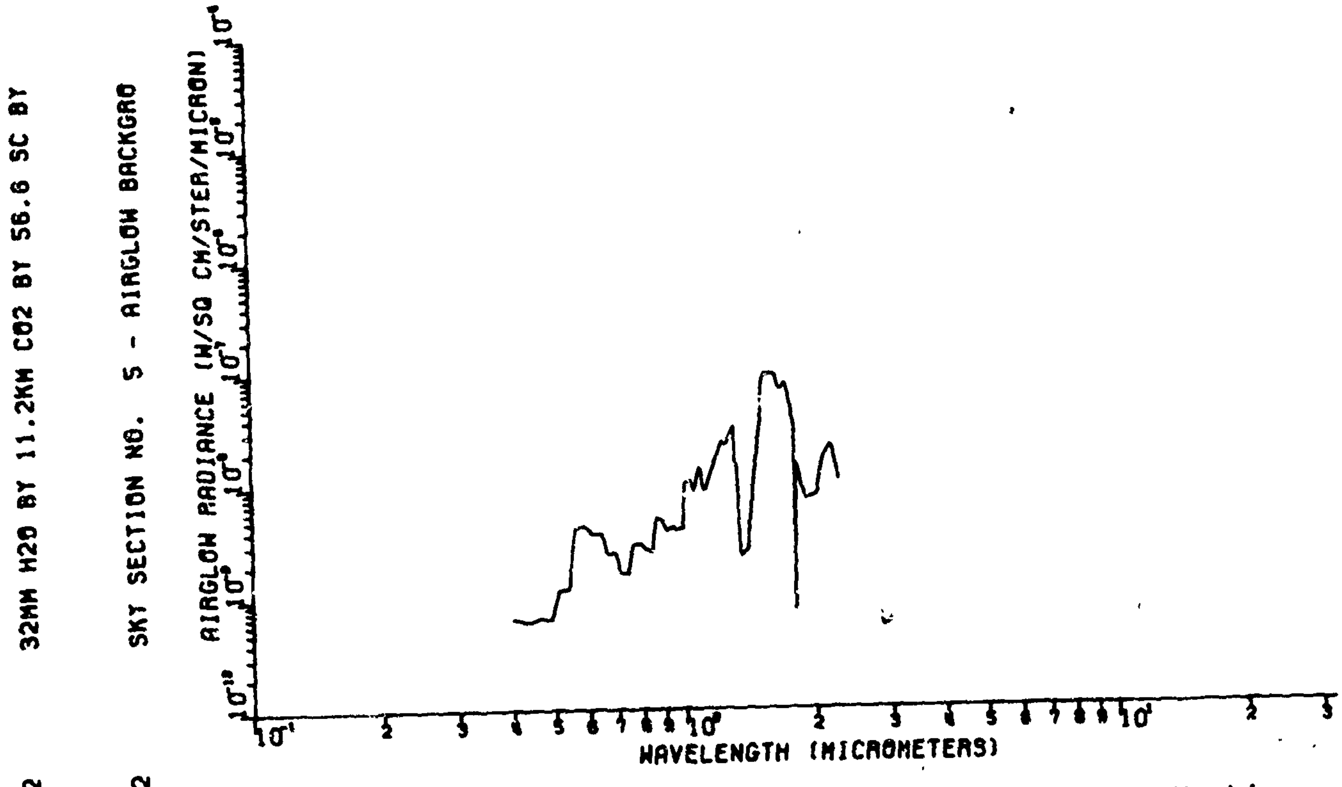


Figure 229. Nightglow as a Background for Sky Segment 5, Zenith Angle of 56.6°

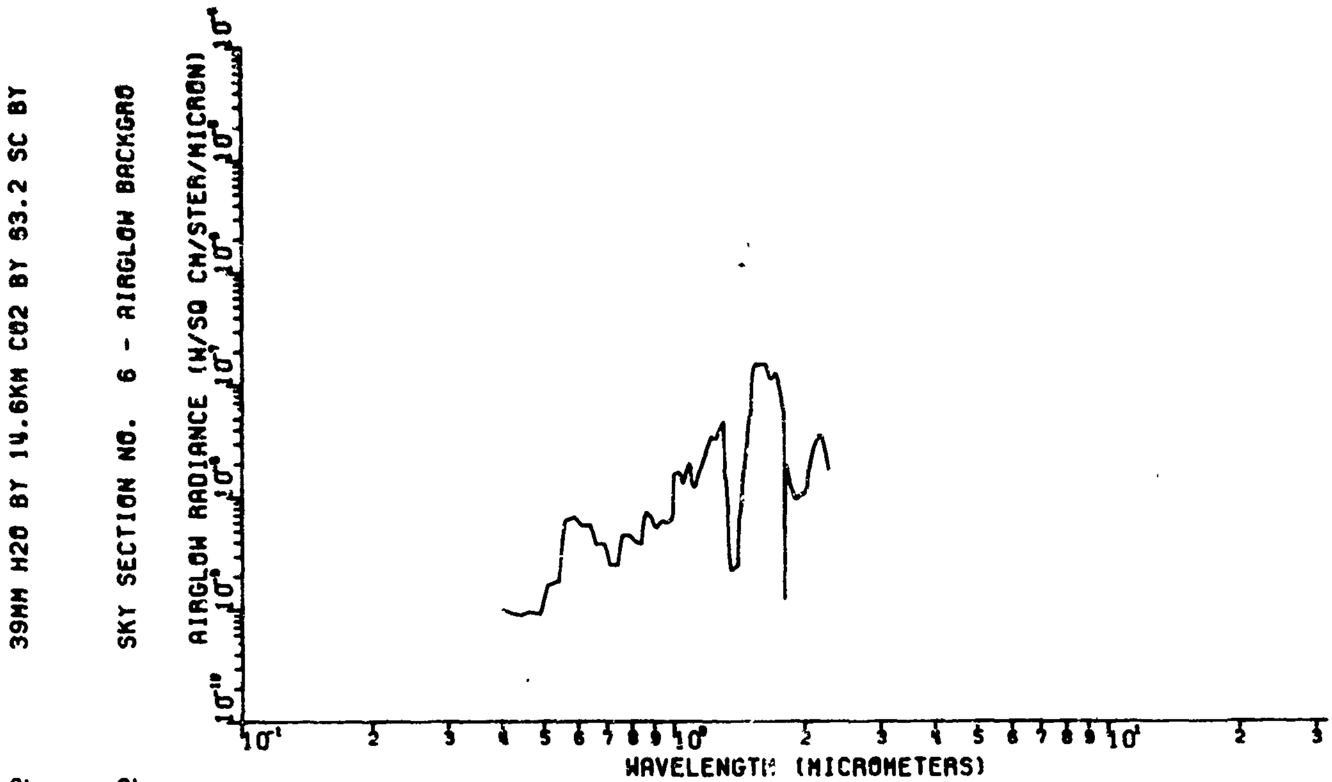


Figure 230. Nightglow as a Background for Sky Segment 6, Zenith Angle of 63.2°

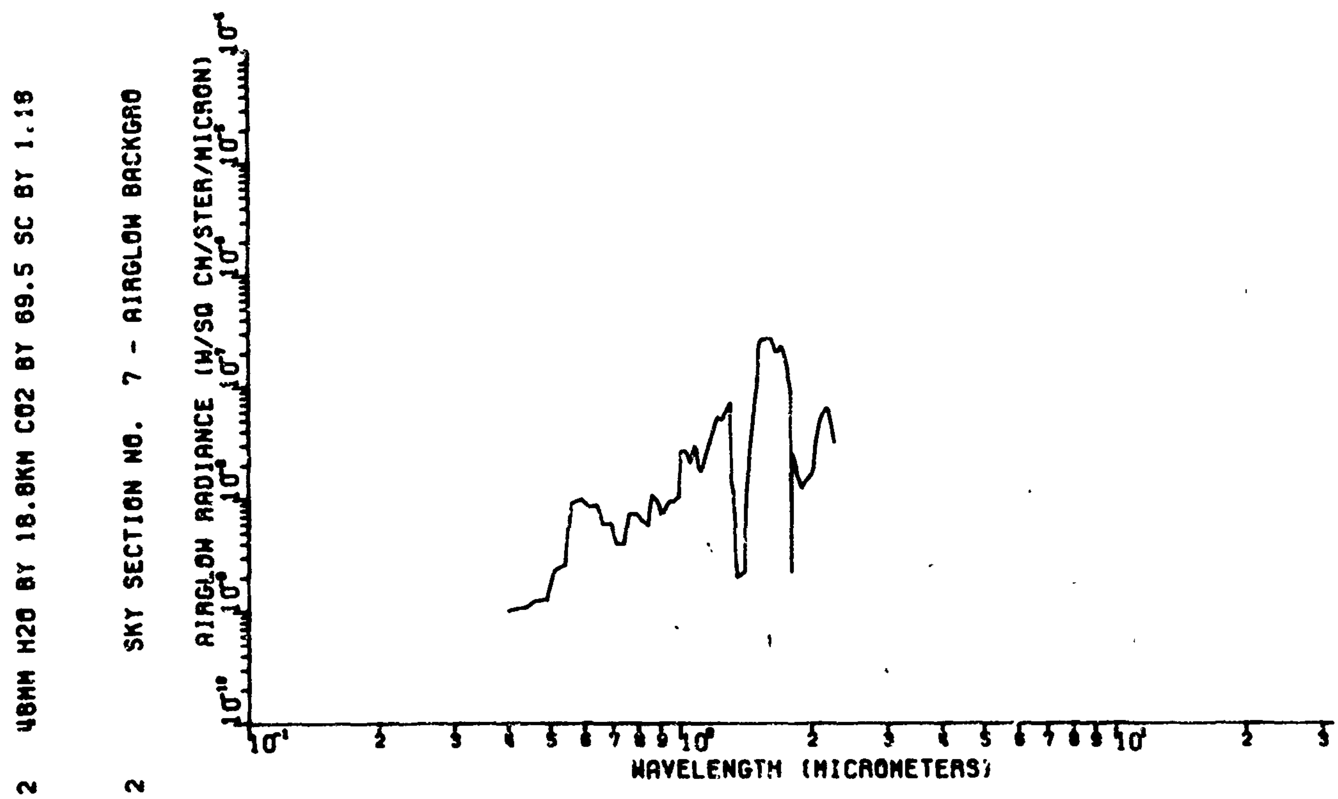


Figure 231. Nightglow as a Background for Sky Segment 7, Zenith Angle of 69.5°.

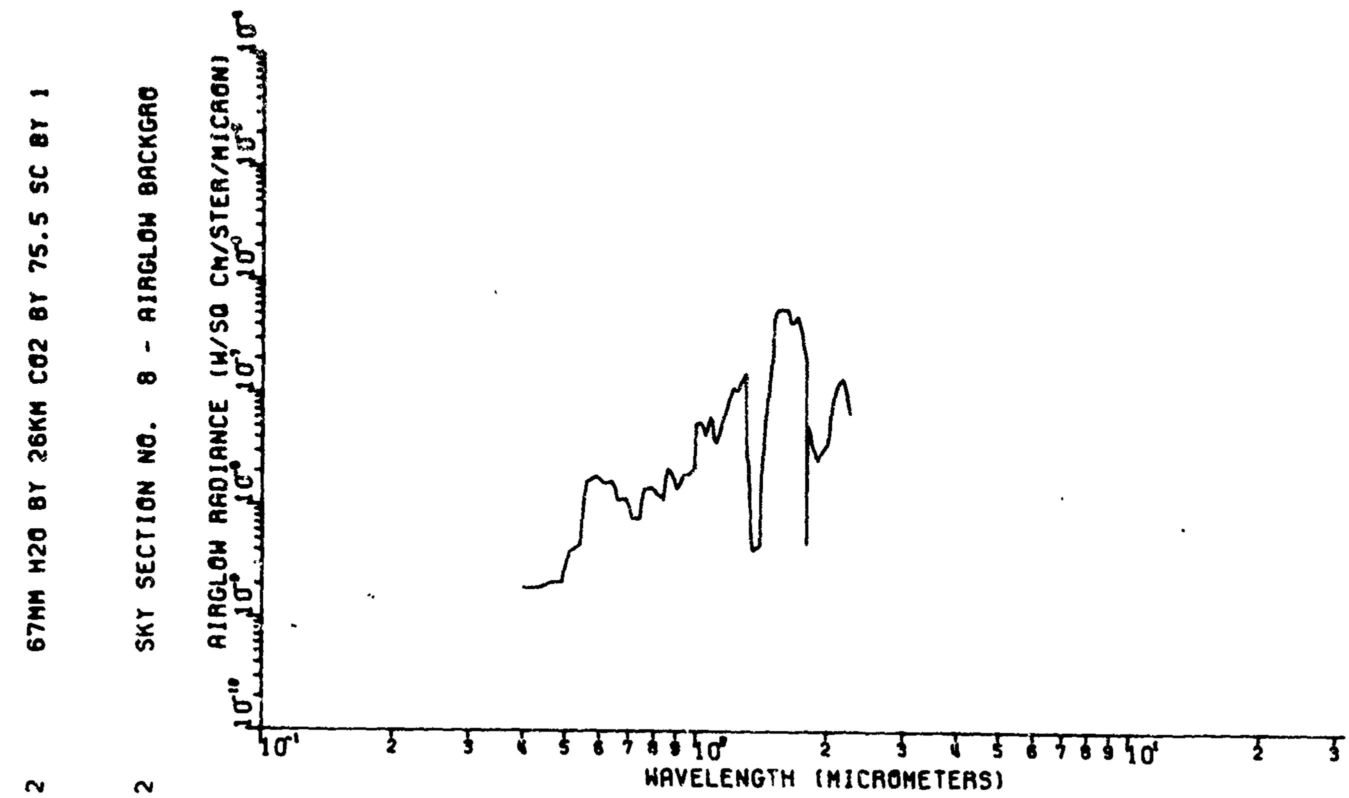


Figure 232. Nightglow as a Background for Sky Segment 8, Zenith Angle of 75.5°

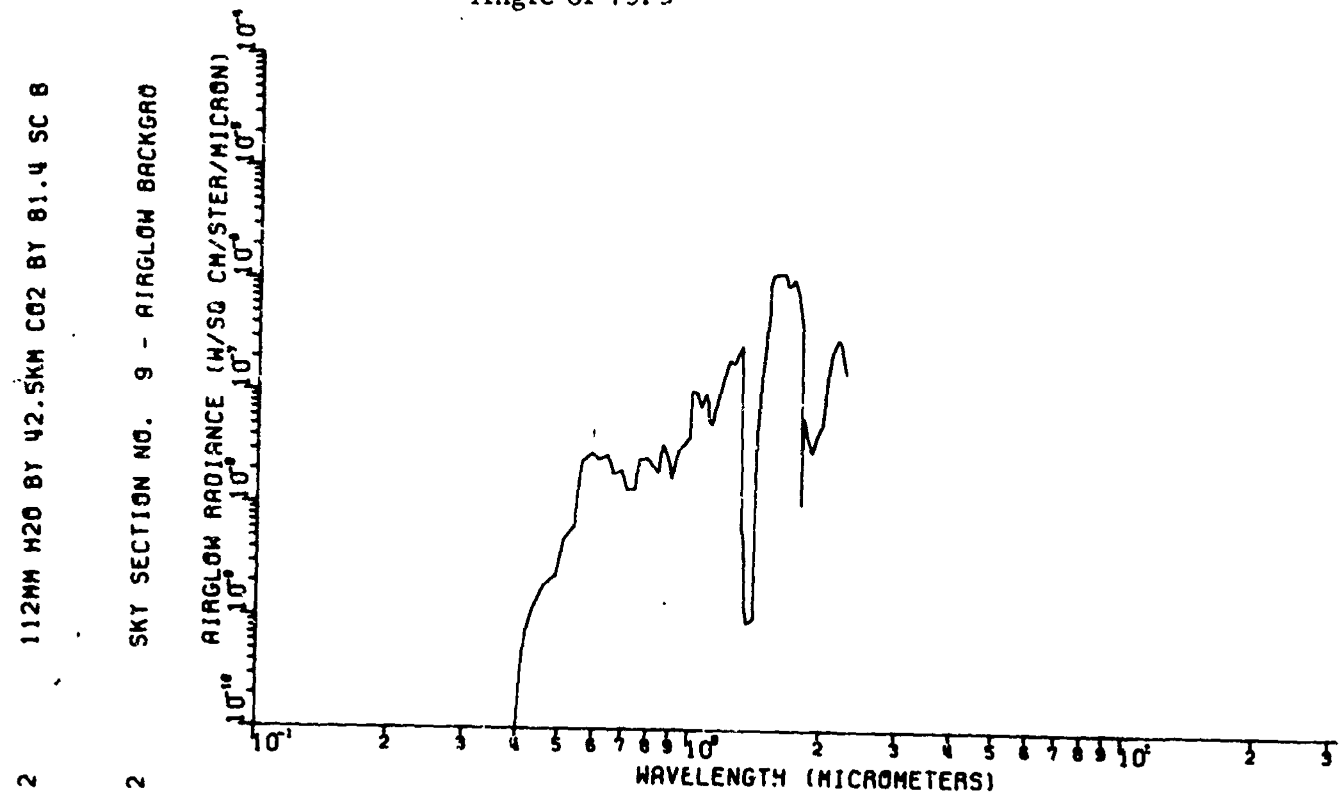


Figure 233. Nightglow as a Background for Sky Segment 9, Zenith Angle of 81.4°

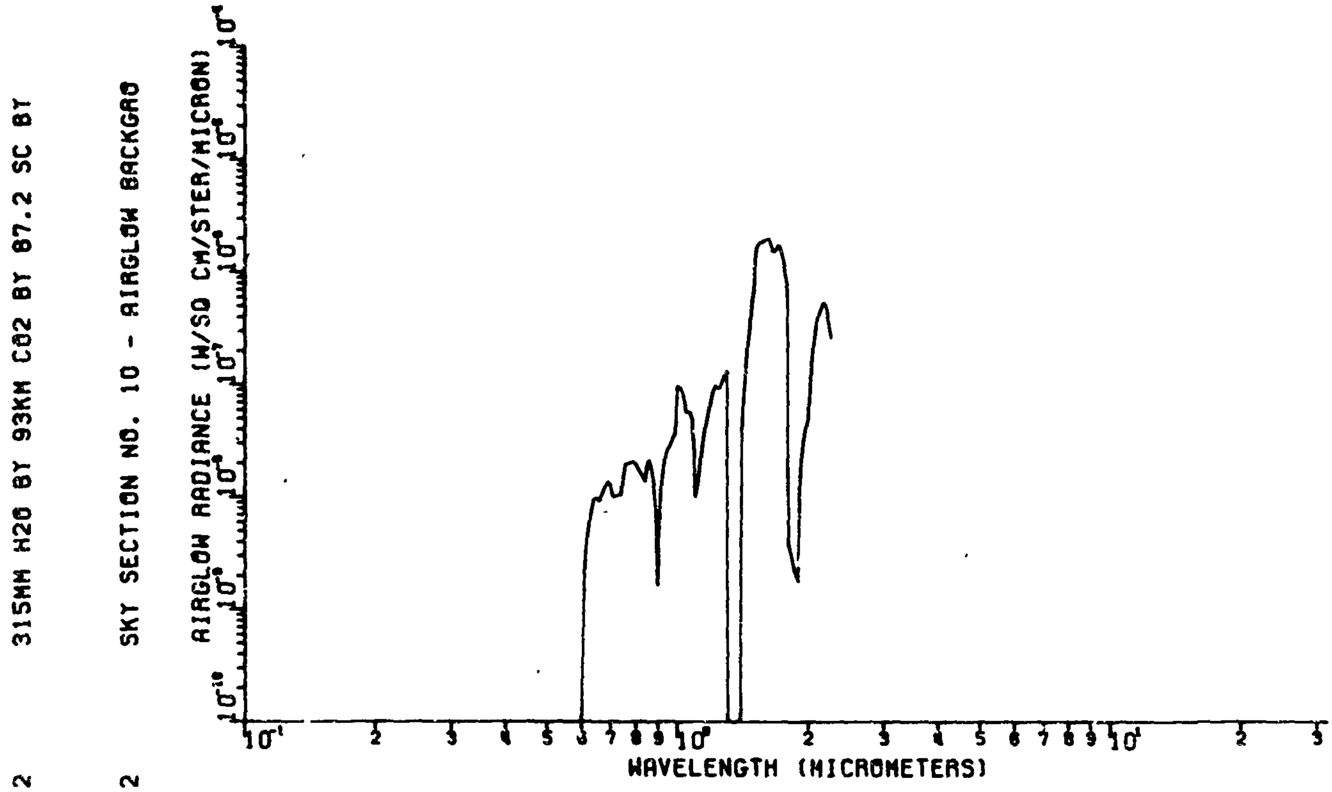


Figure 234. Nightglow as a Background for Sky Segment 10, Zenith Angle of 87.2°

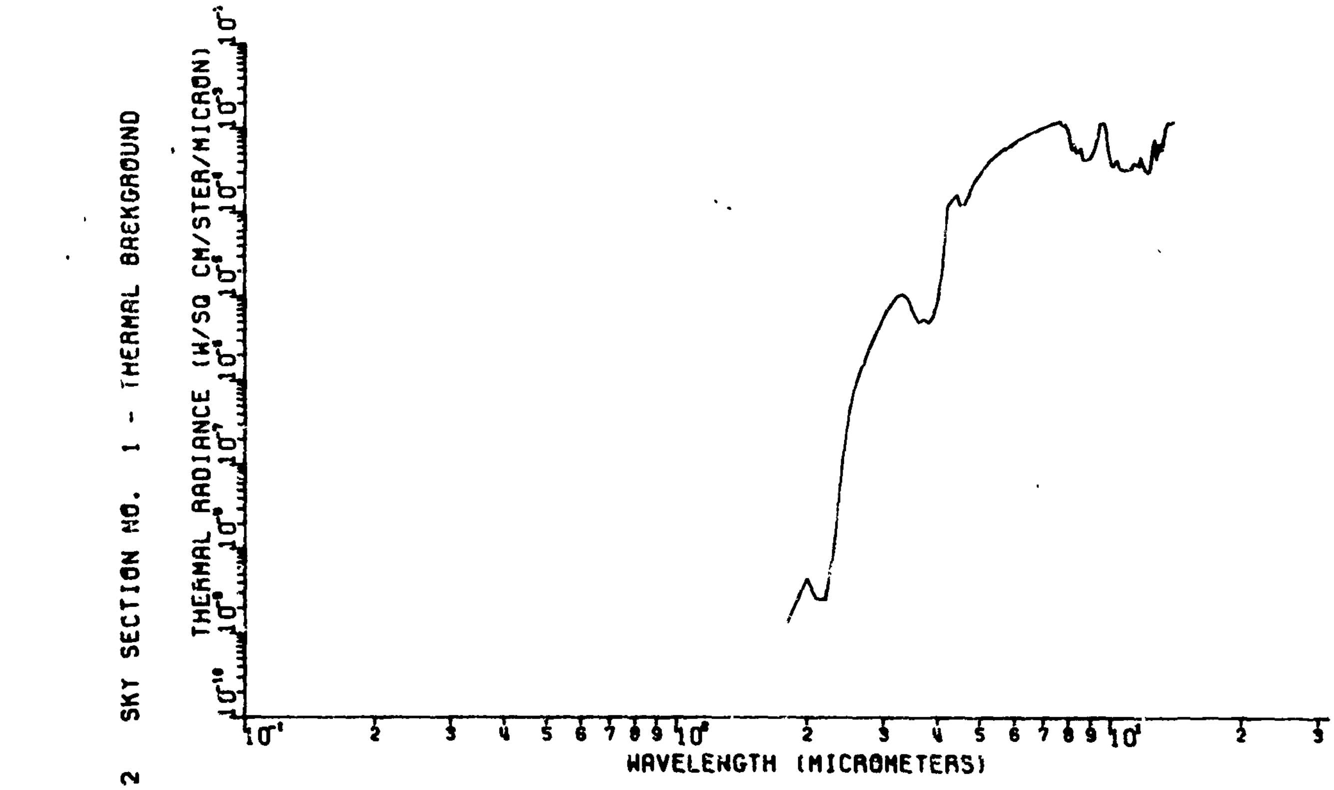


Figure 235. Tropospheric Thermal Energy as a Background for Sky Segment 1, Zenith Angle of 18.1°

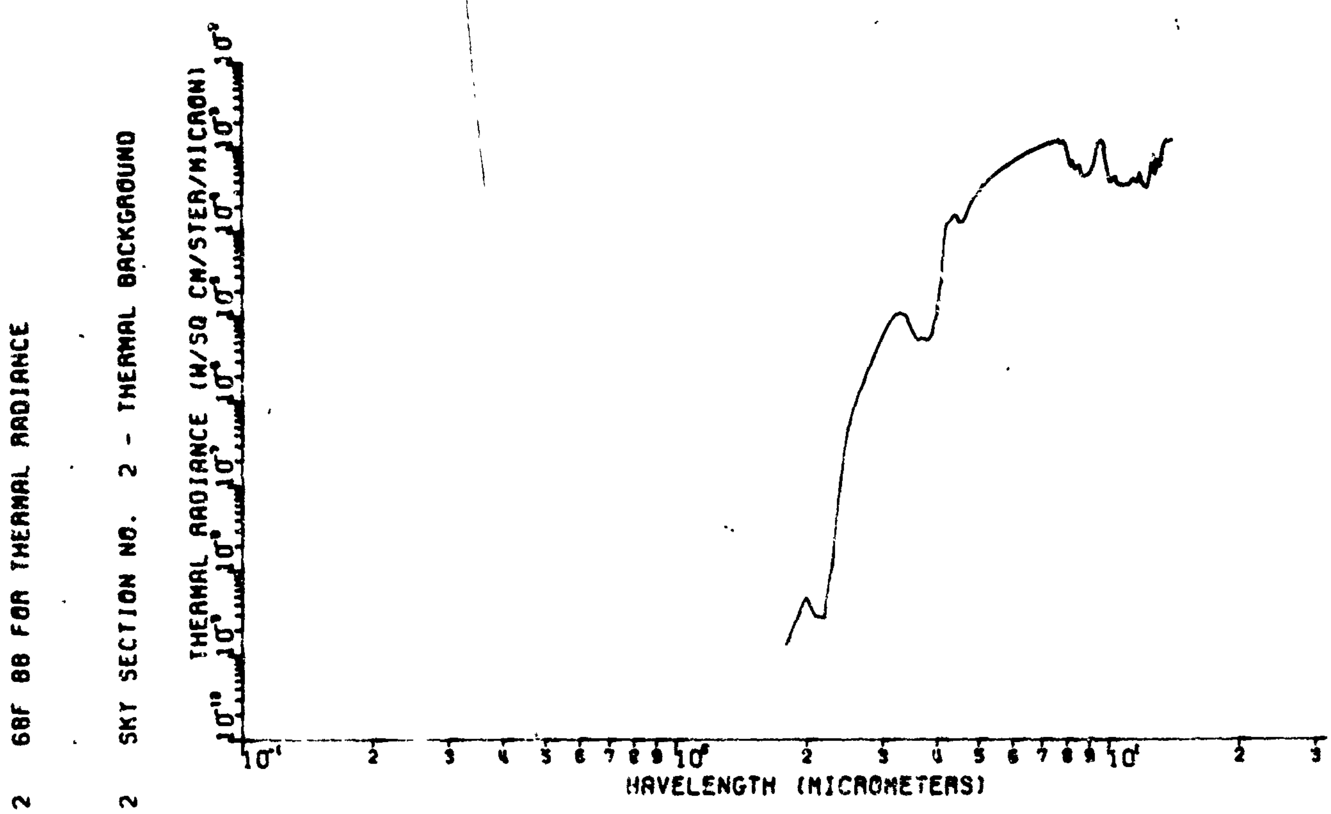


Figure 236. Tropospheric Thermal Energy as a Background for Sky Segment 2, Zenith Angle of 31.7°

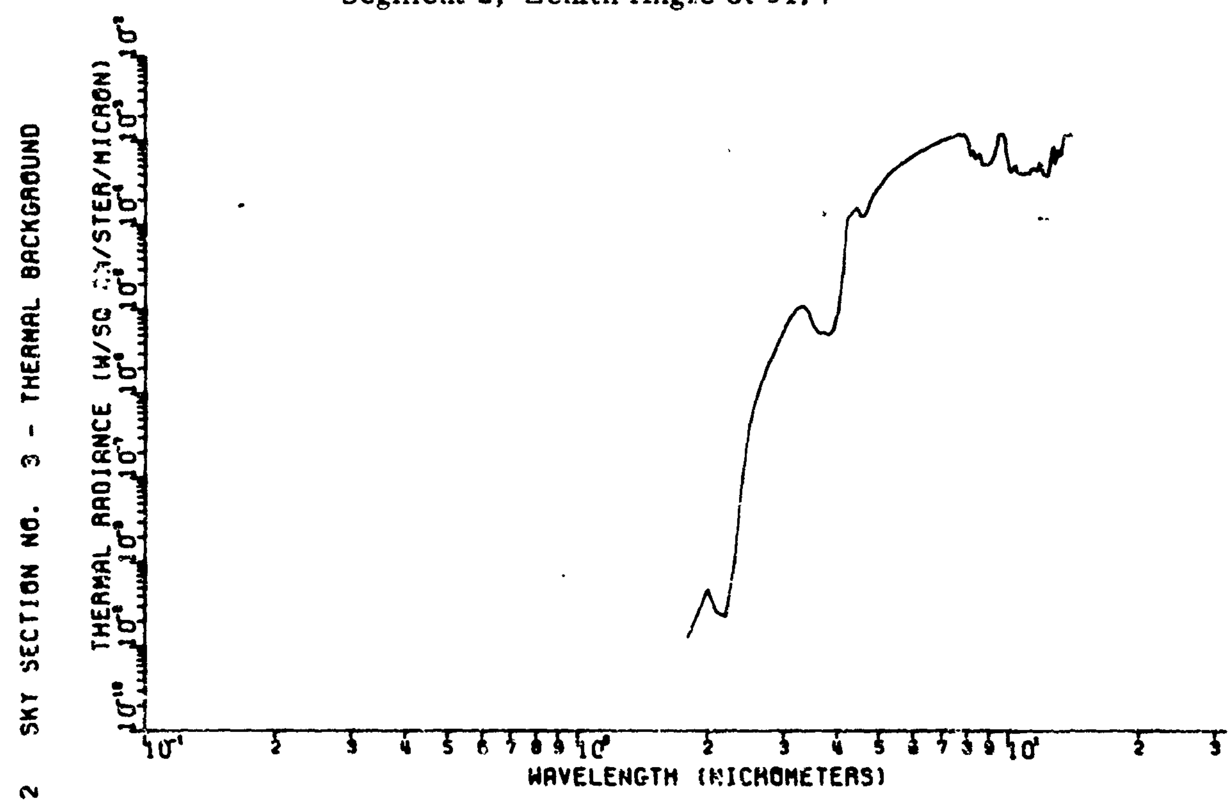


Figure 237. Tropospheric Thermal Energy as a Background for Sky Segment 3, Zenith Angle of 41.4°

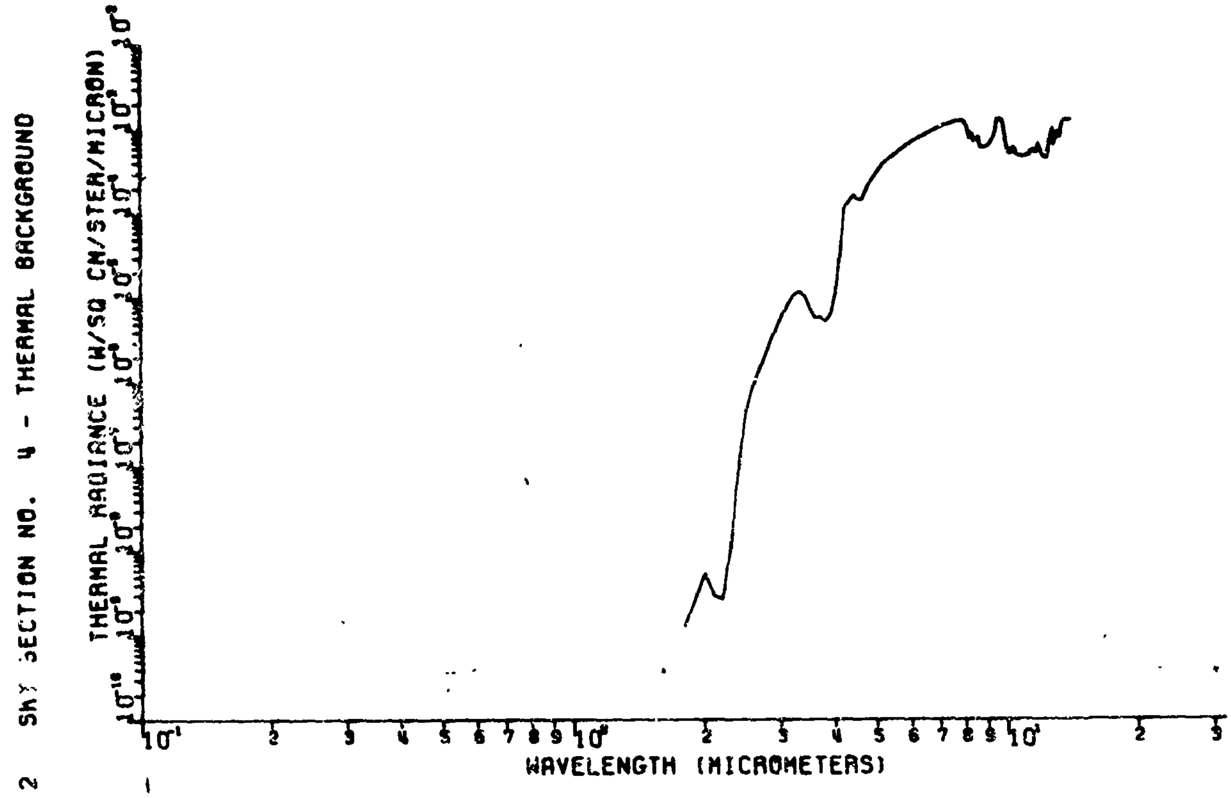


Figure 238. Tropospheric Thermal Energy as a Background for Sky Segment 4, Zenith Angle of 49.5°

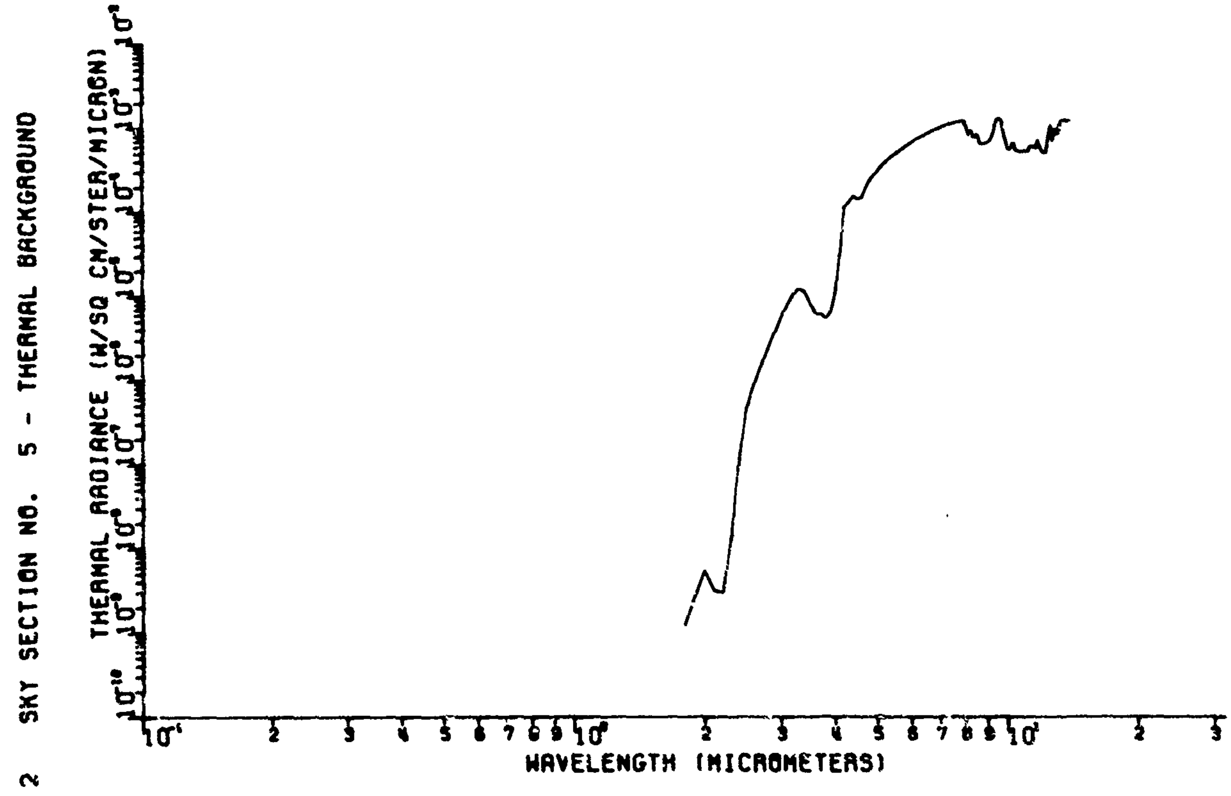


Figure 239. Tropospheric Thermal Energy as a Background for Sky Segment 5, Zenith Angle of 56.6°

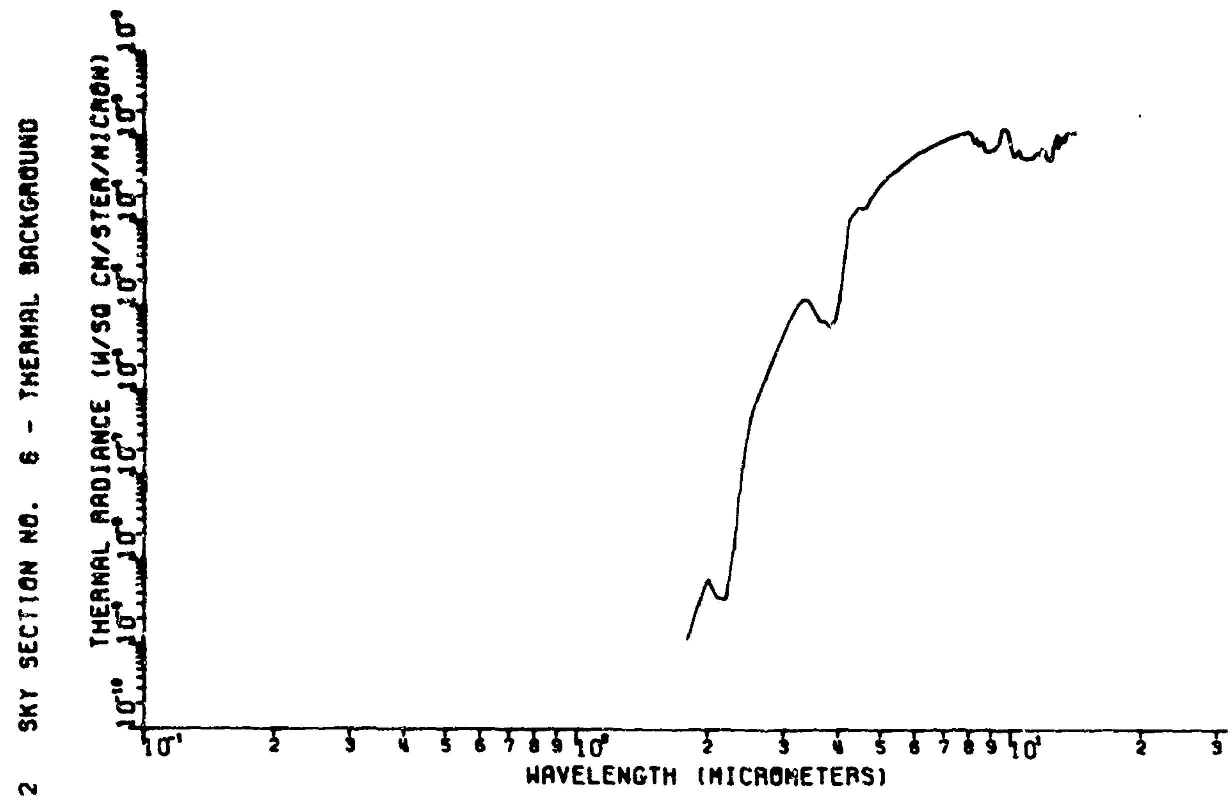


Figure 240. Tropospheric Thermal Energy as a Background for Sky Segment 6, Zenith Angle of 63.2°

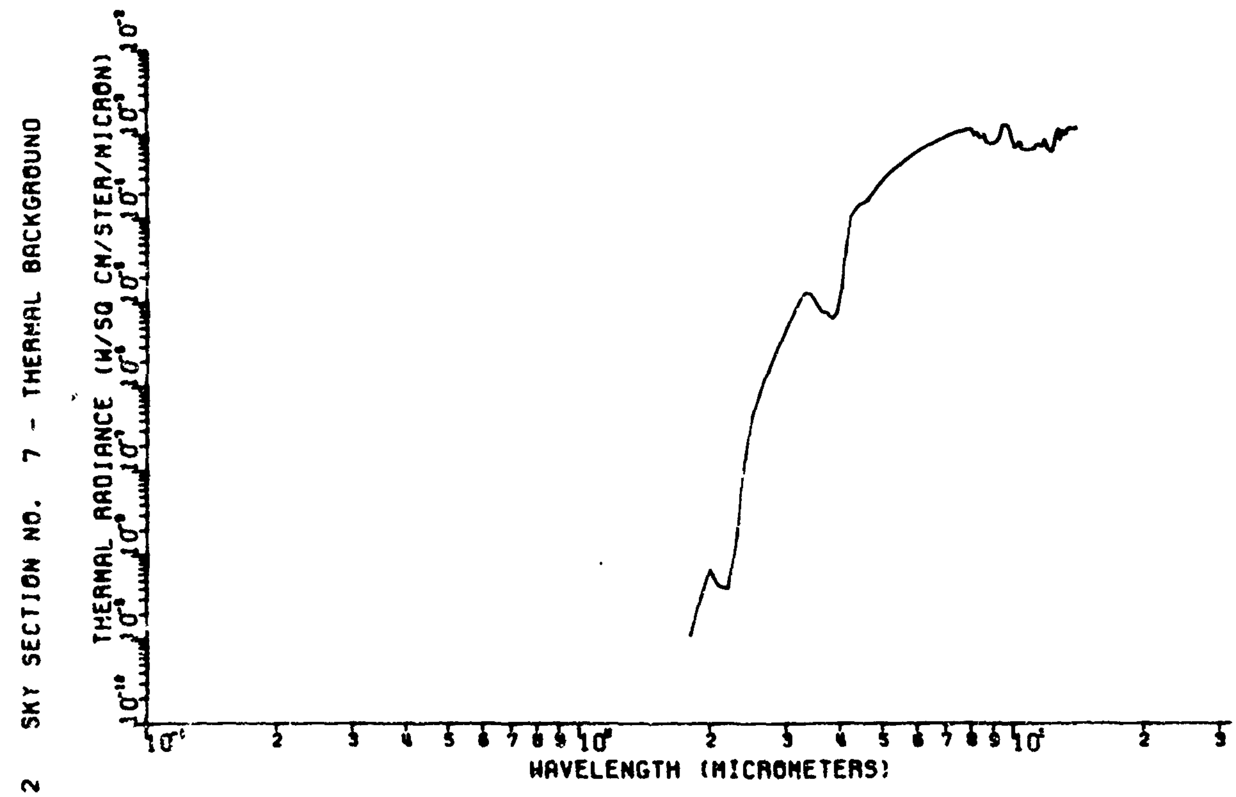


Figure 241. Tropospheric Thermal Energy as a Background for Sky Segment 7, Zenith Angle of 69.5°

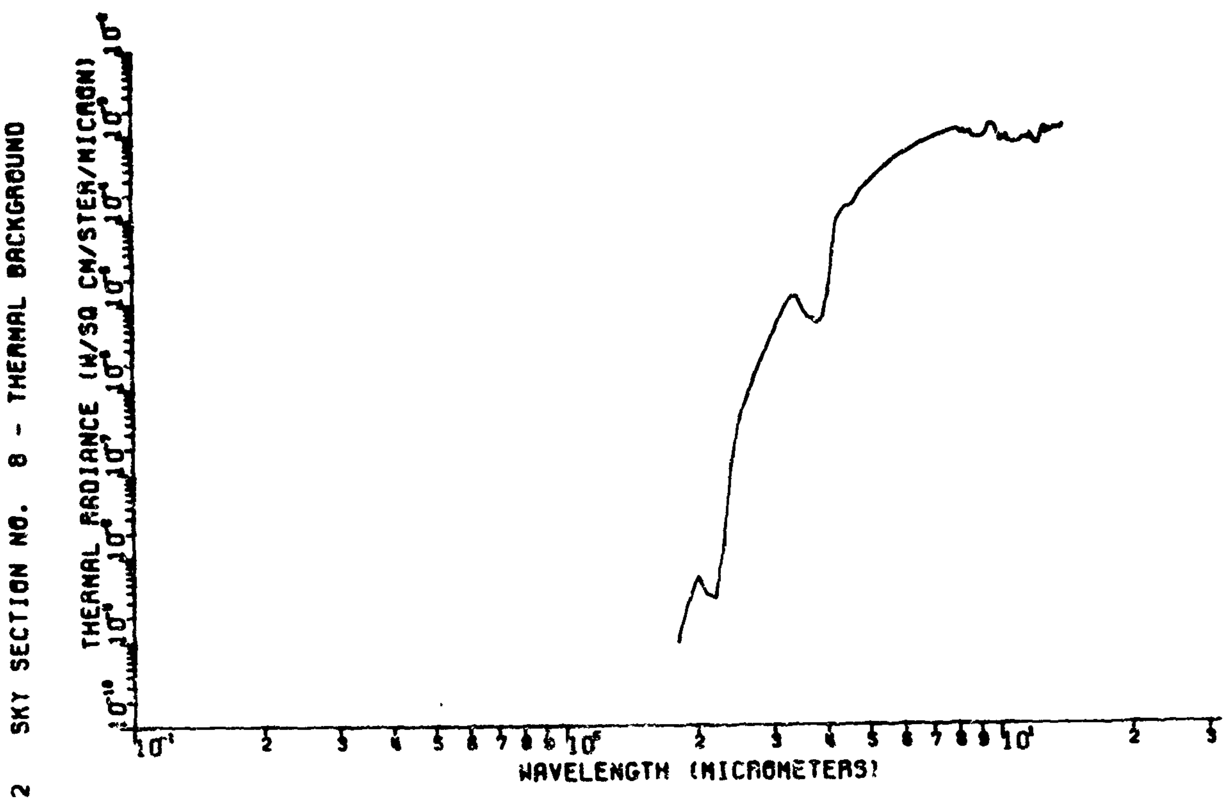


Figure 242. Tropospheric Thermal Energy as a Background for Sky Segment 8, Zenith Angle of 75.5°

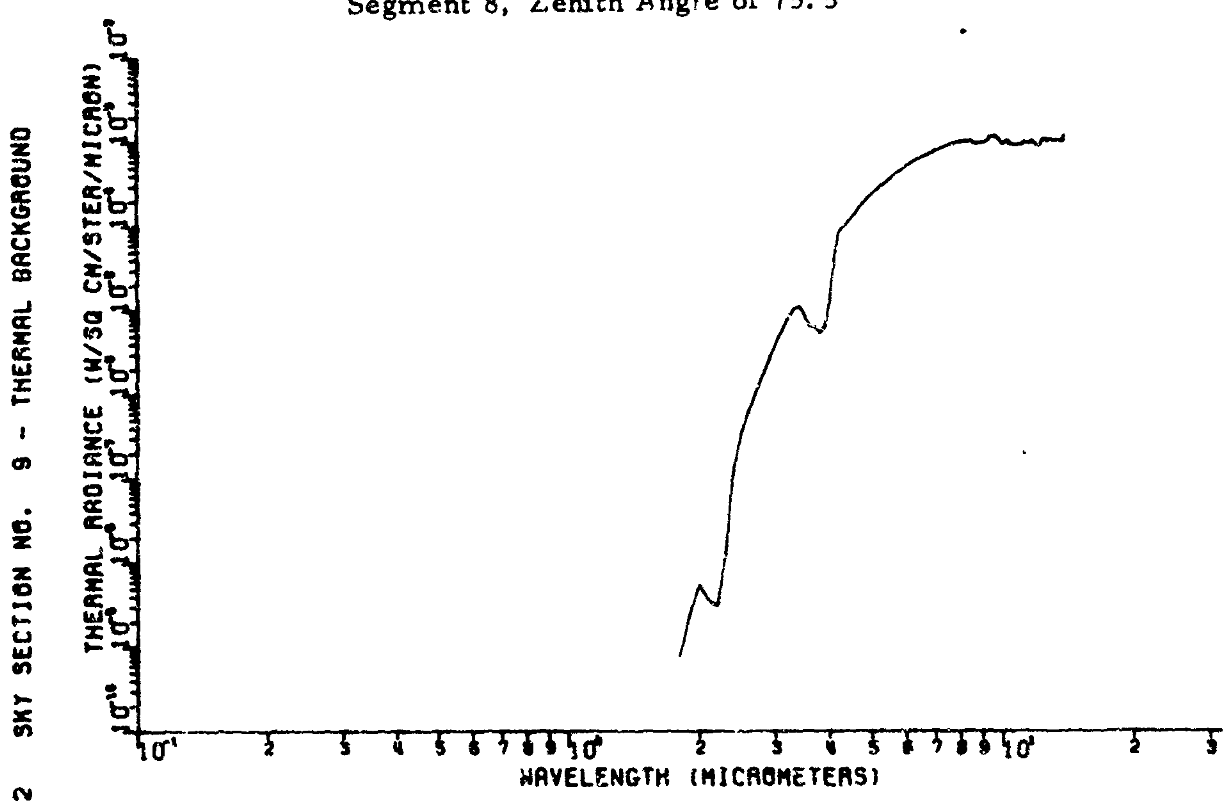


Figure 243. Tropospheric Thermal Energy as a Background for Sky Segment 9, Zenith Angle of 81.4°

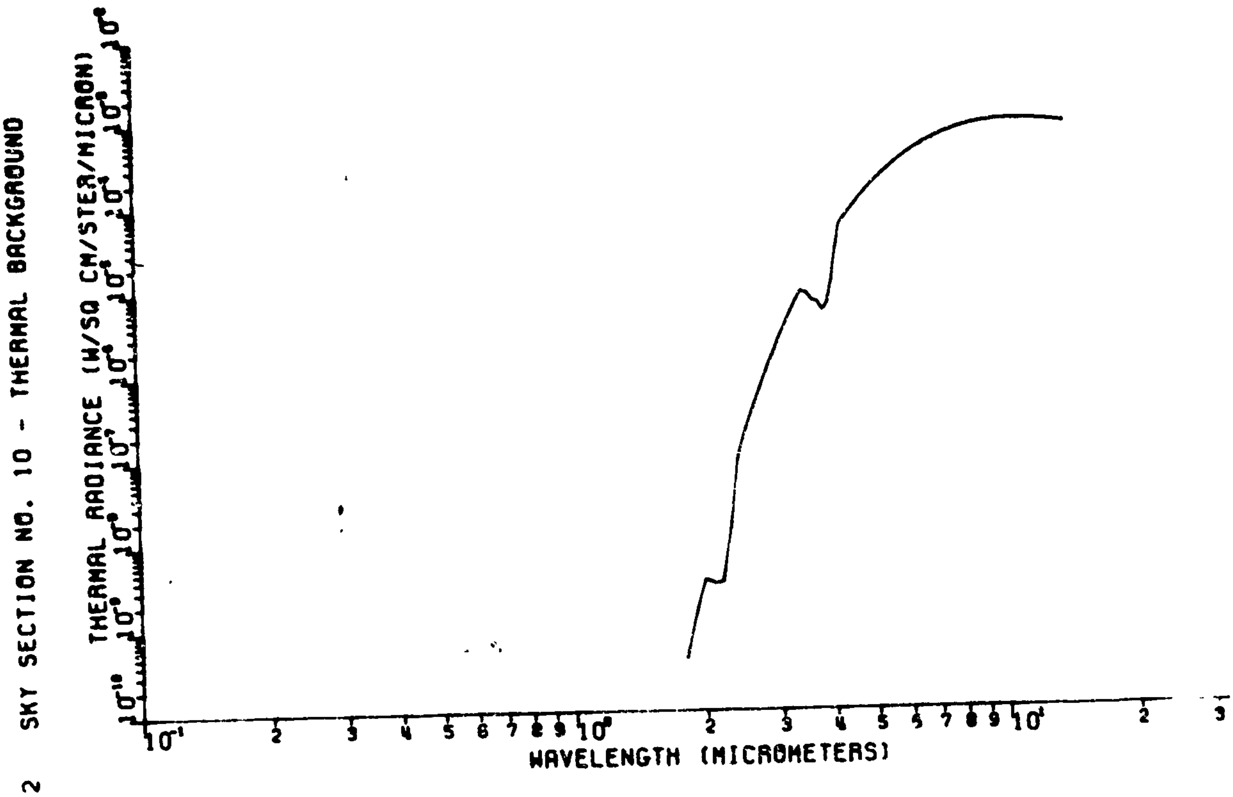


Figure 244. Tropospheric Thermal Energy as a Background for Sky Segment 10, Zenith Angle of 87.2°

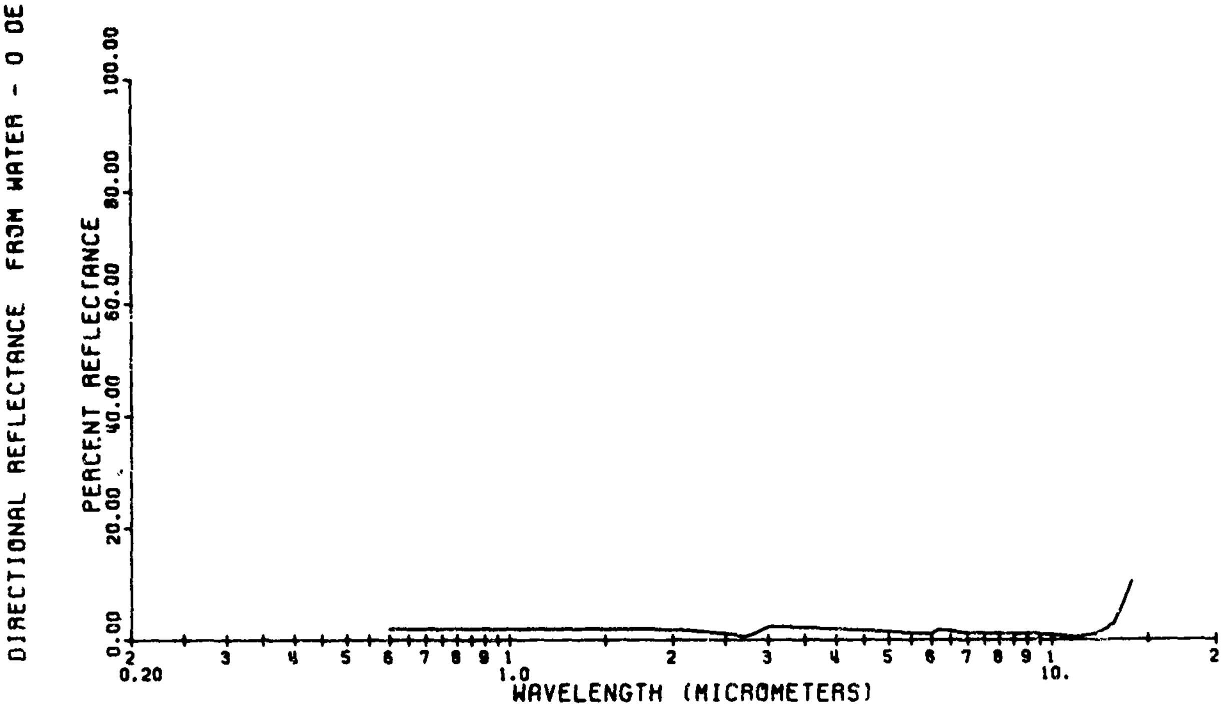


Figure 247. Sea Water Reflectance for an Incident Angle of 0°

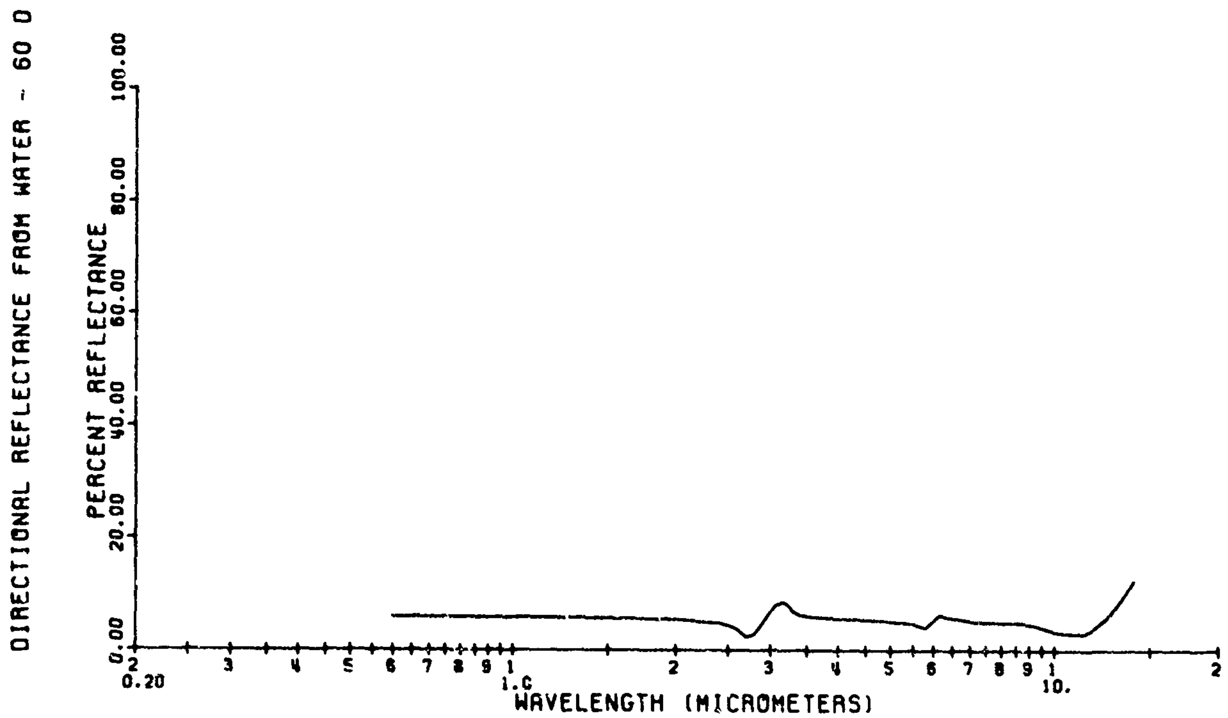


Figure 248. Sea Water Reflectance for an Incident Angle of 60°

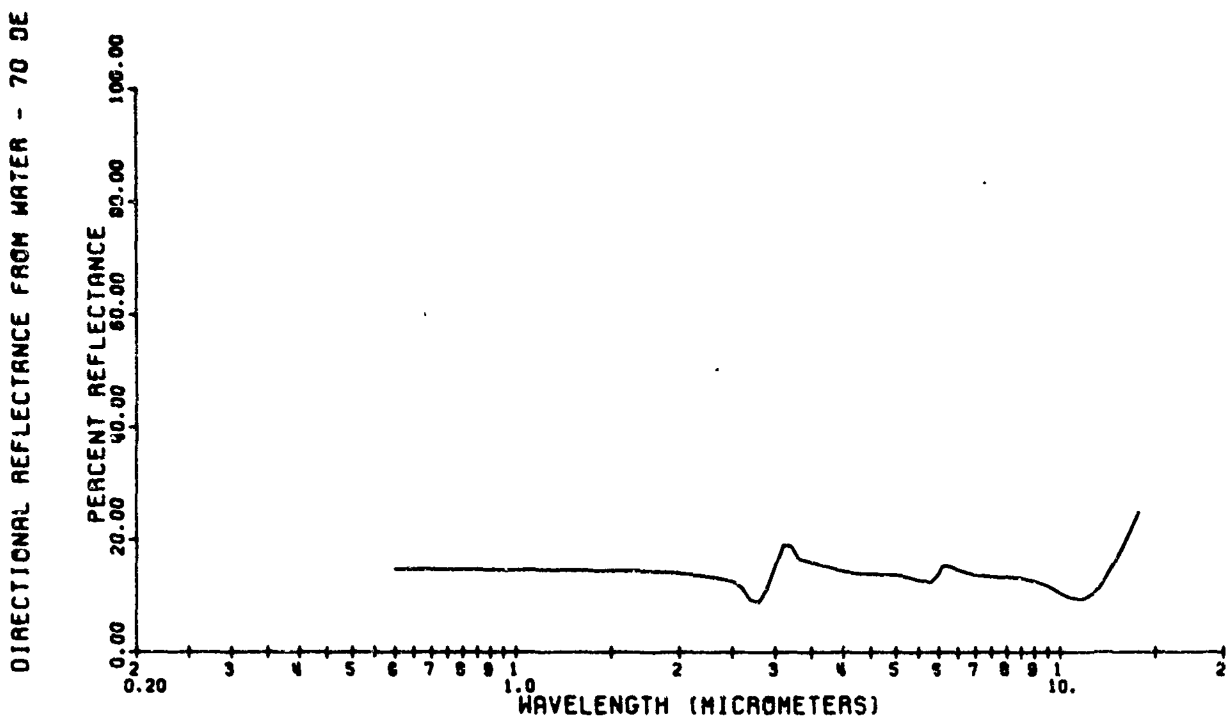


Figure 249. Sea Water Reflectance for an Incident Angle of 70°

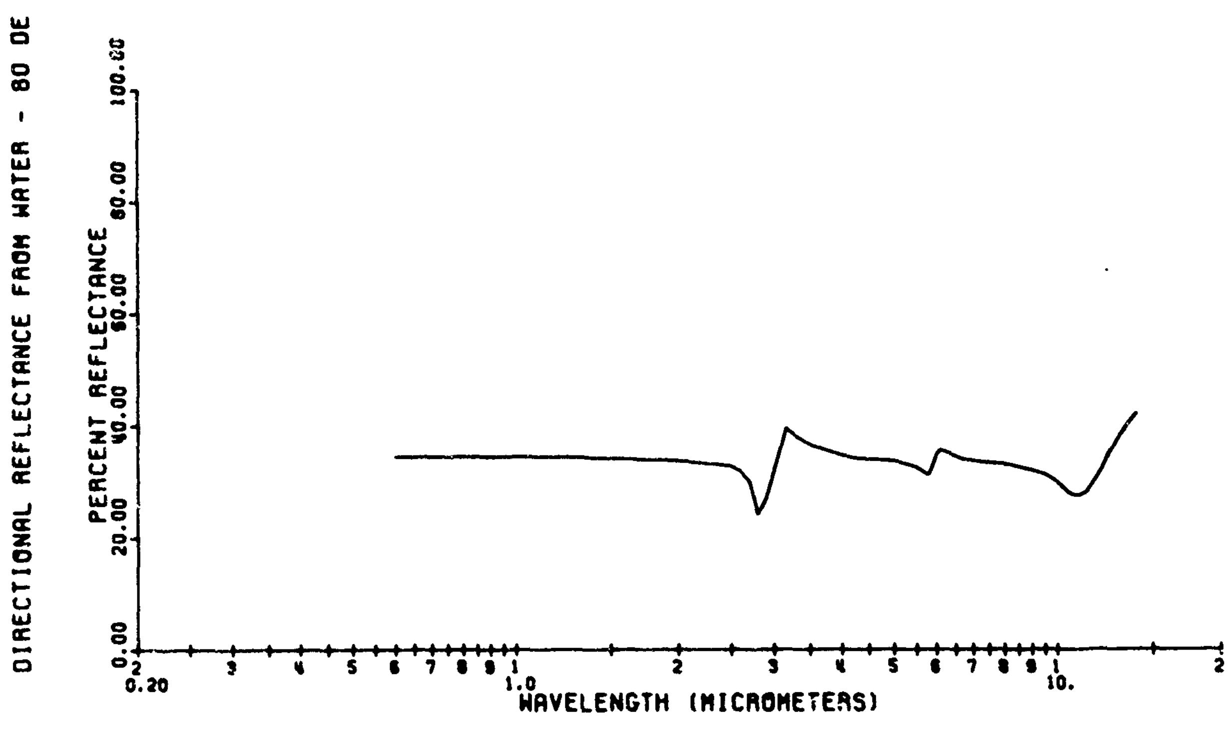


Figure 250. Sea Water Reflectance for an Incident Angle of 80°

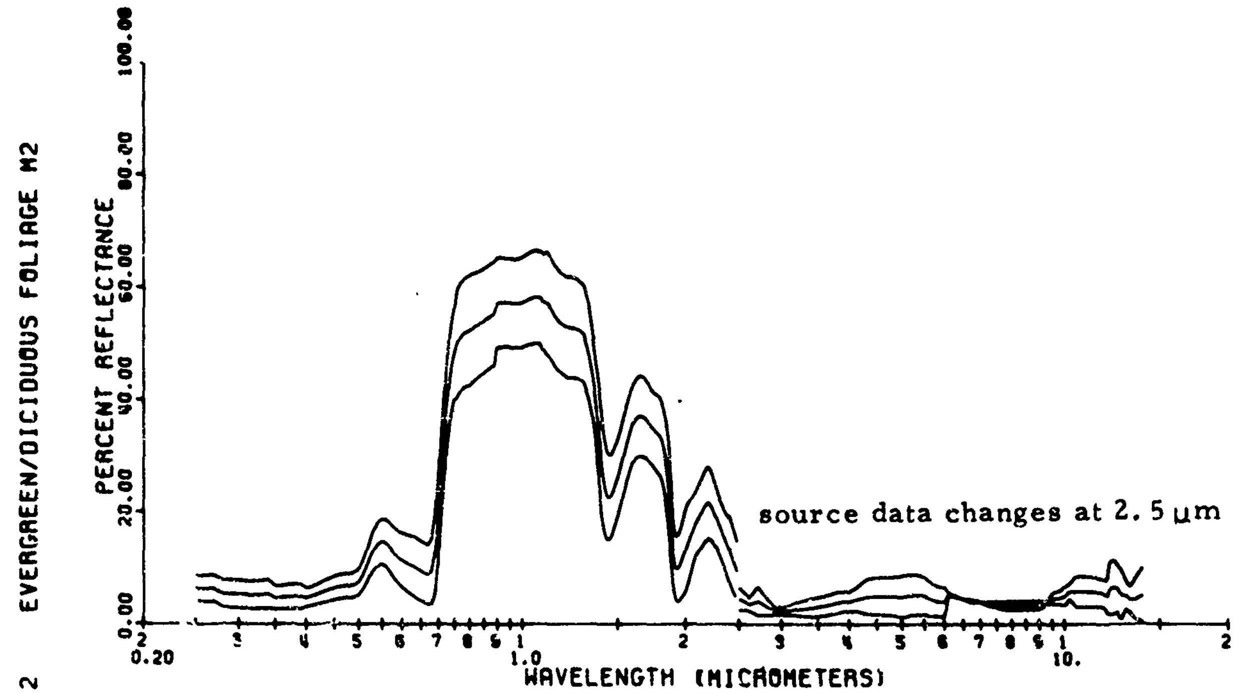


Figure 252. Spectral Reflectance of Live Deciduous/Tropical Evergreen/ Palmaceous Tree Foliage

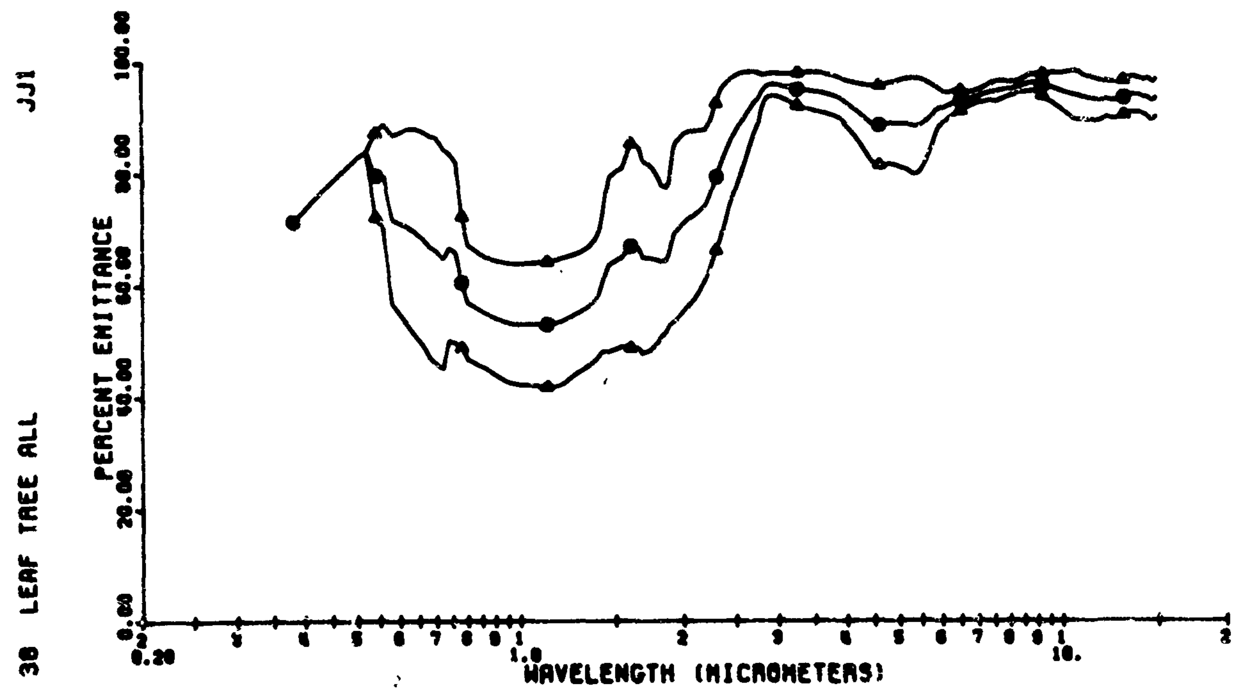


Figure 253. Spectral Emittance of Live Deciduous/Tropical Evergreen/ Palmaceous Tree Foliage

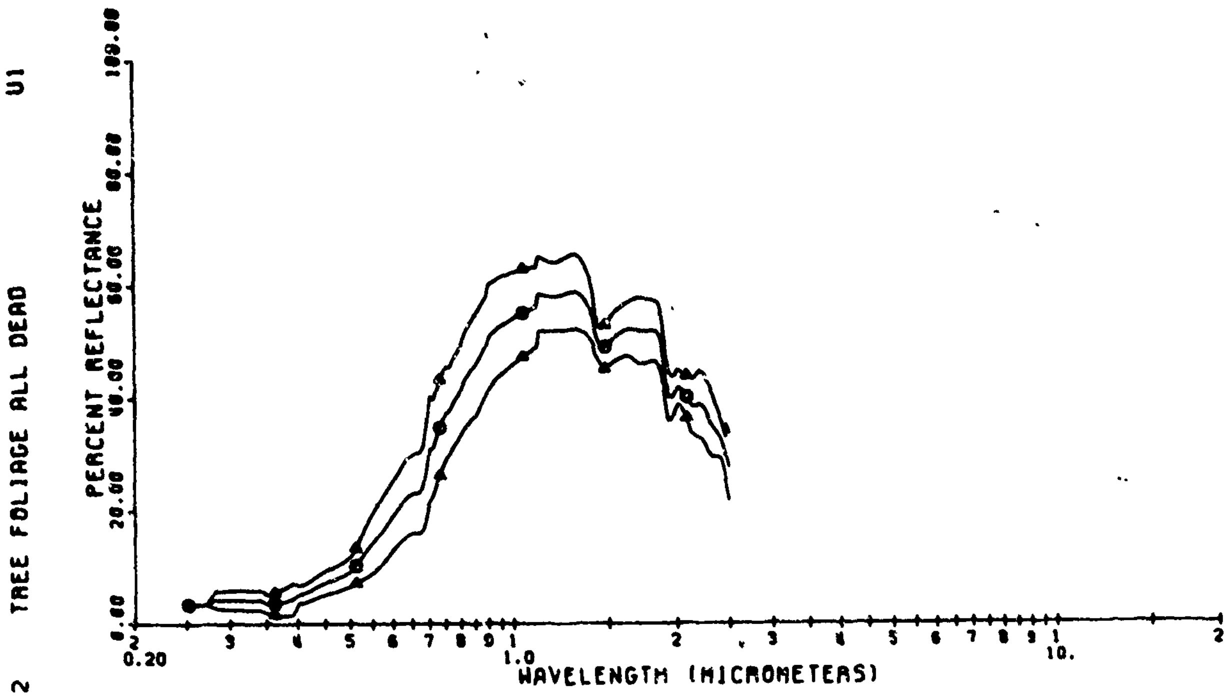


Figure 254. Spectral Reflectance of Dead Deciduous/Tropical Evergreen/ Palmaceous Tree Foliage

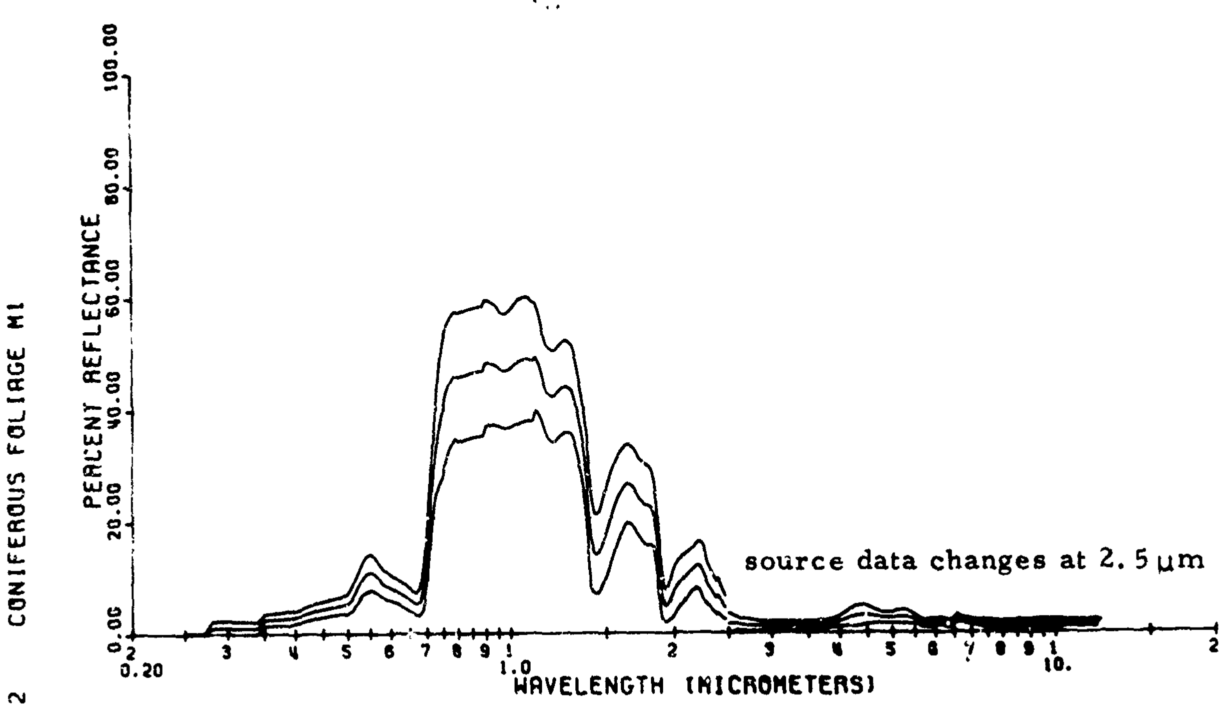


Figure 255. Spectral Reflectance of Live Coniferous Needles

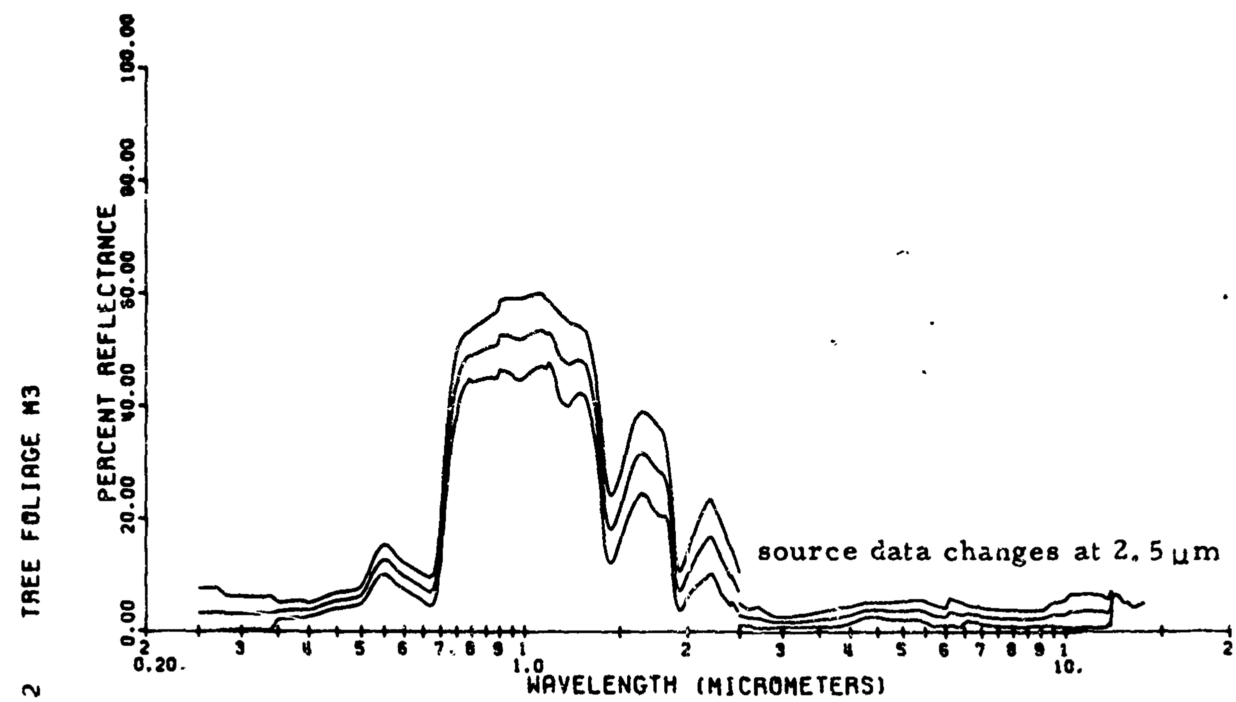


Figure 256. Spectral Reflectance of All Live Tree Foliage

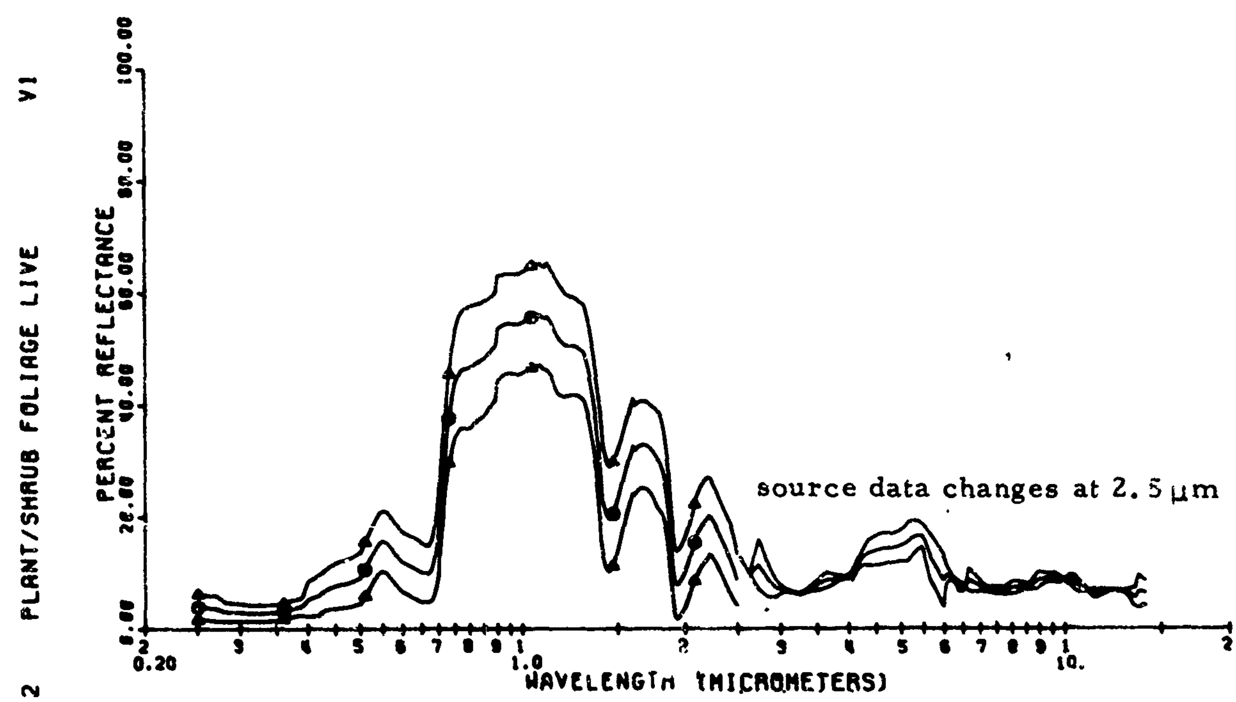


Figure 257. Spectral Reflectance of Live Plant/Shrub Foliage

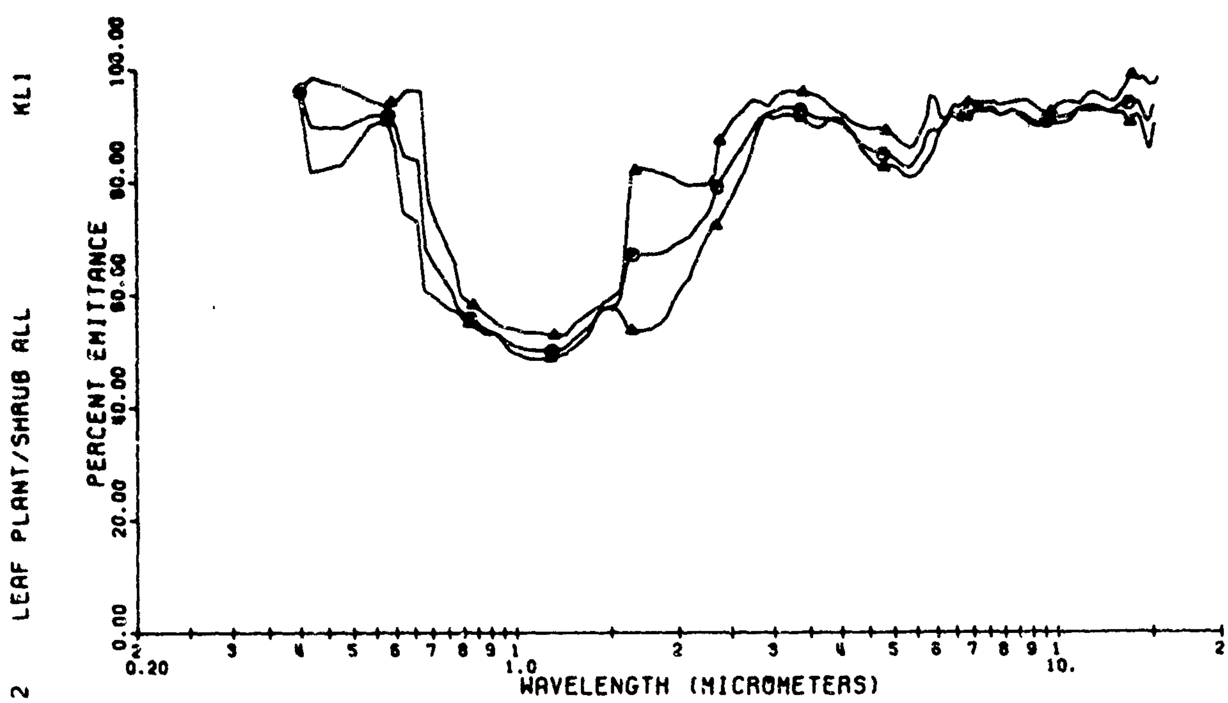


Figure 258. Spectral Emittance of Live Plant/Shrub Foliage

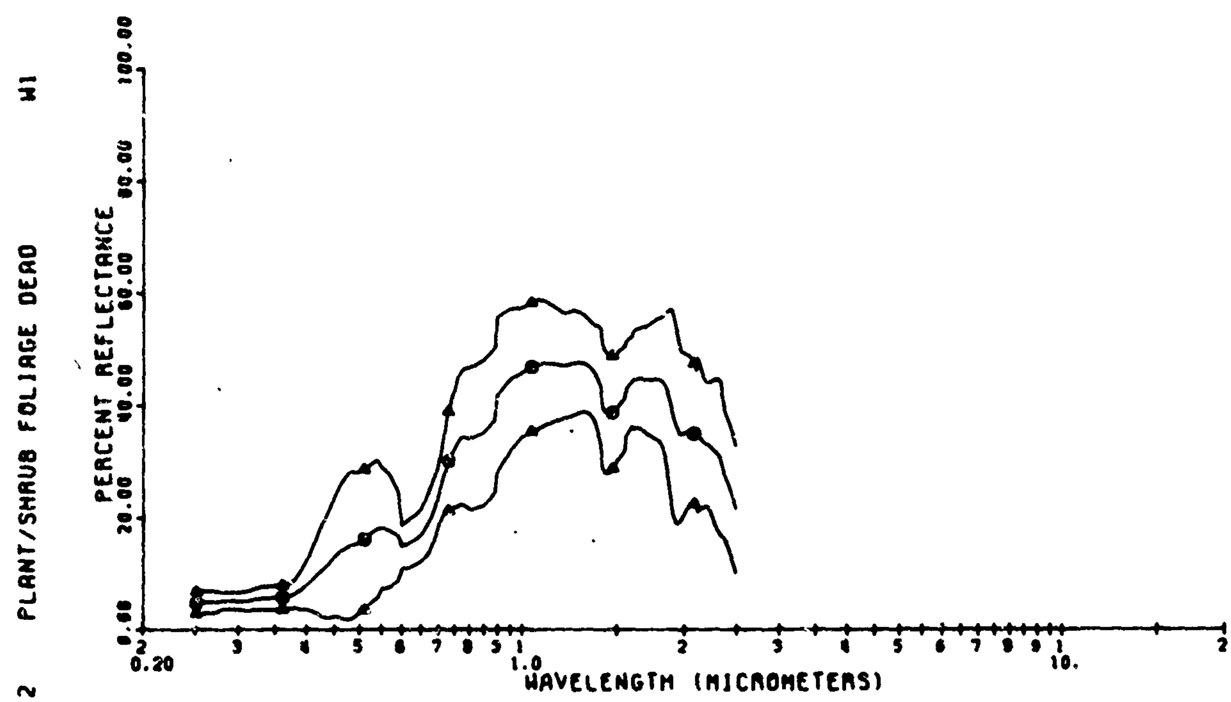


Figure 259. Spectral Reflectance of Dead Plant/Shrub Foliage

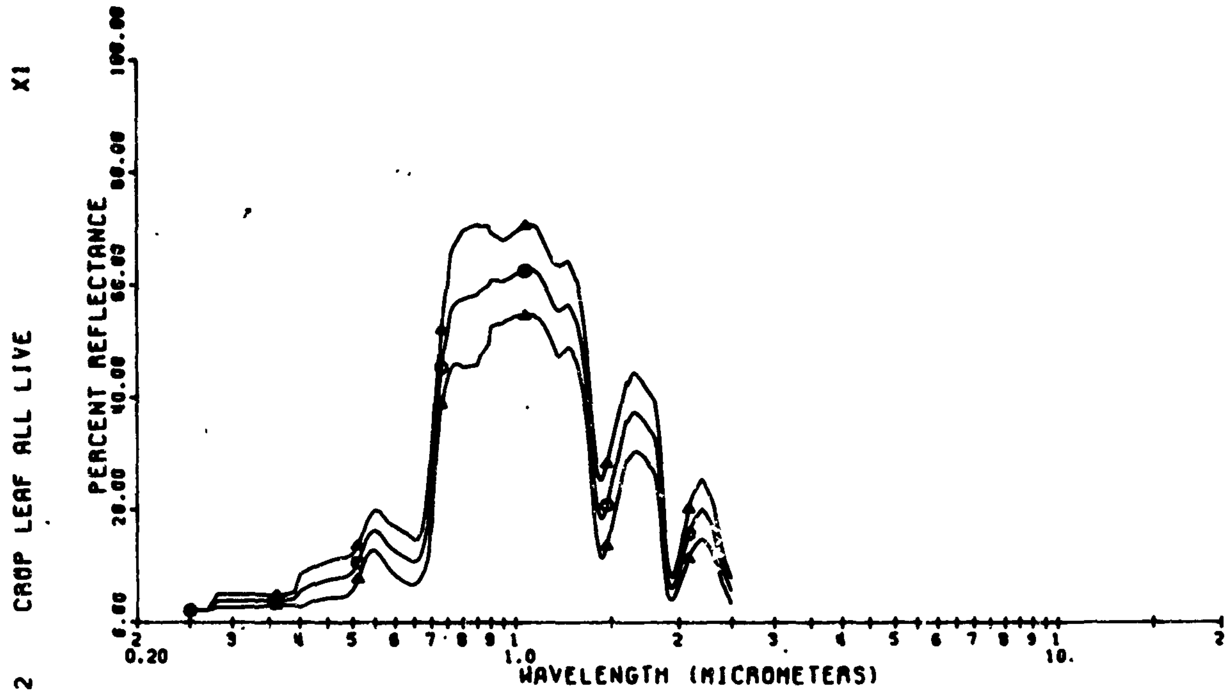


Figure 260. Spectral Reflectance of Live Crop Foliage

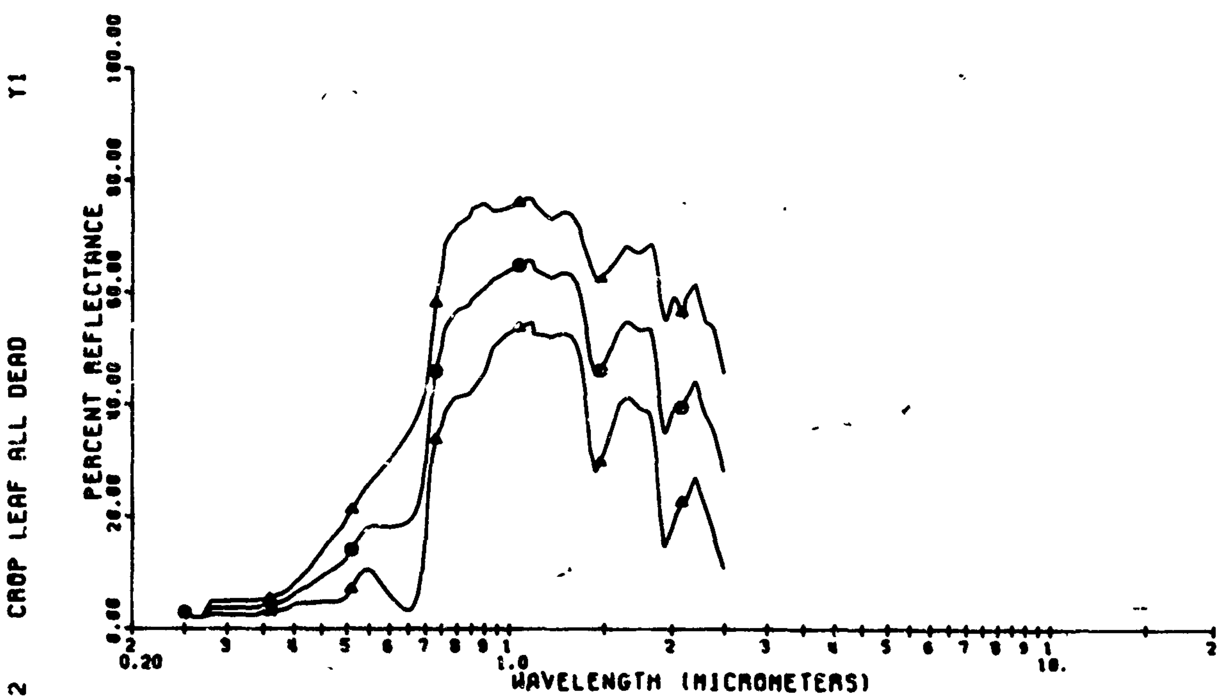


Figure 261. Spectral Reflectance of Dead Crop Foliage

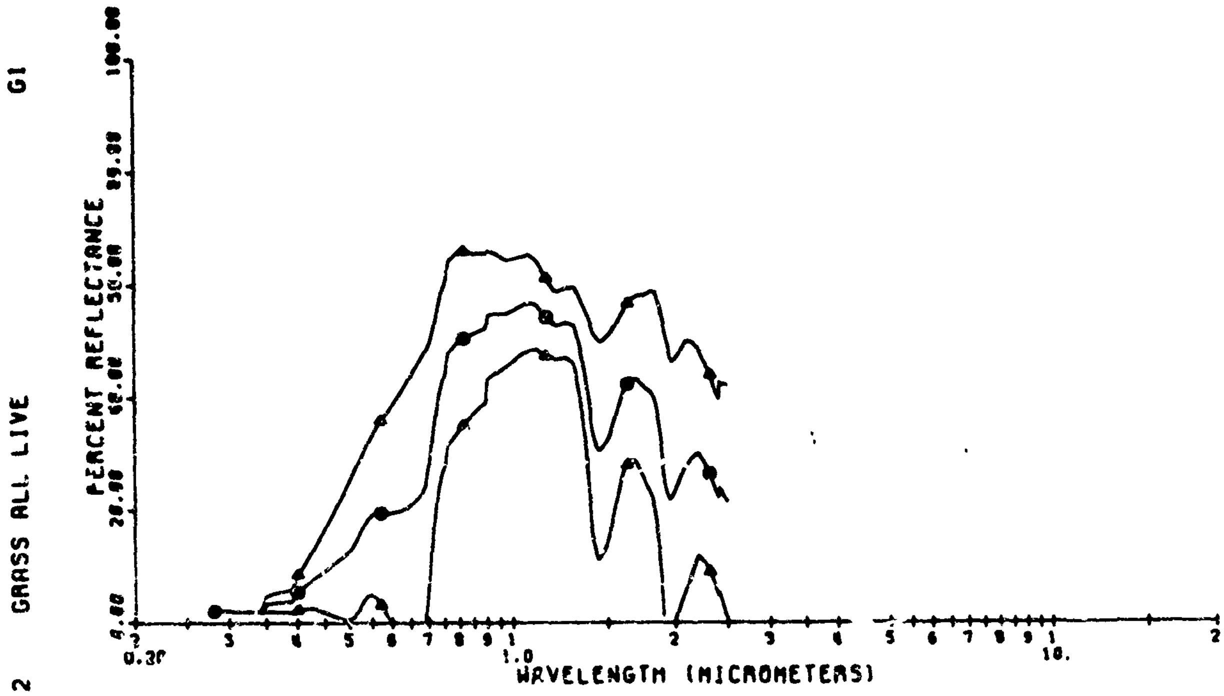


Figure 262. Spectral Reflectance of Live Grasses

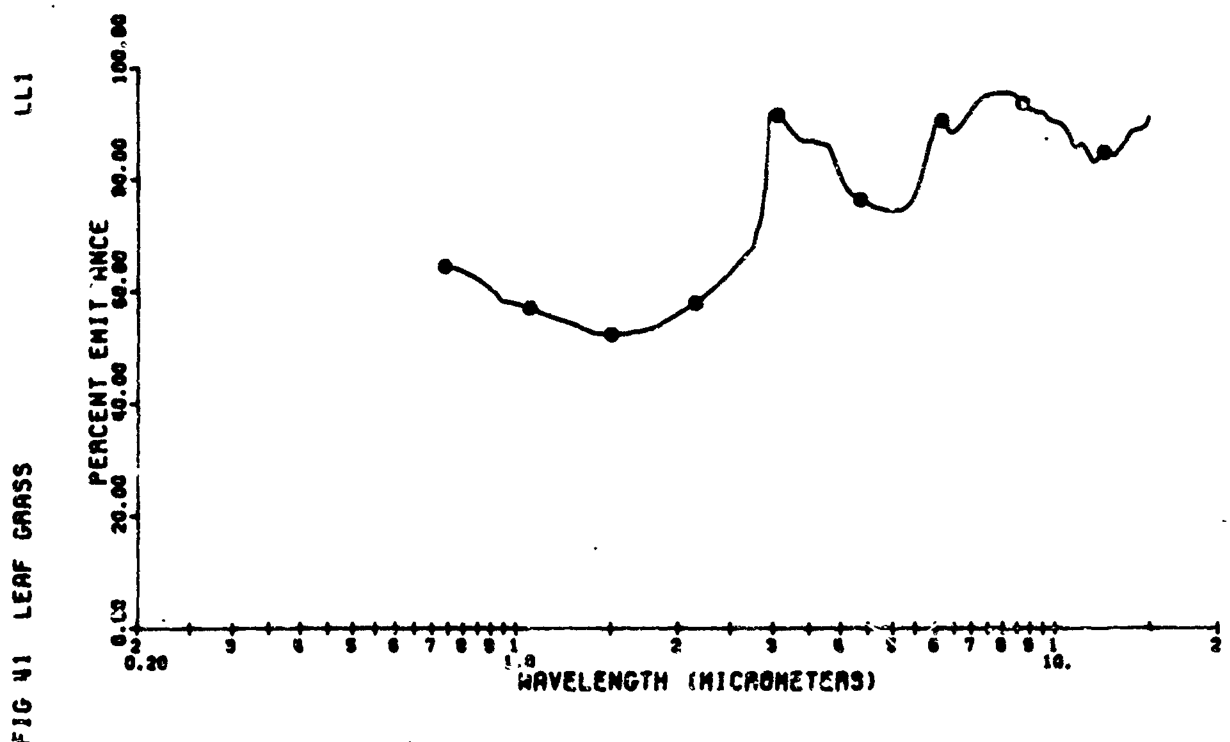


Figure 263. Spectral Emittance of Live Grasses

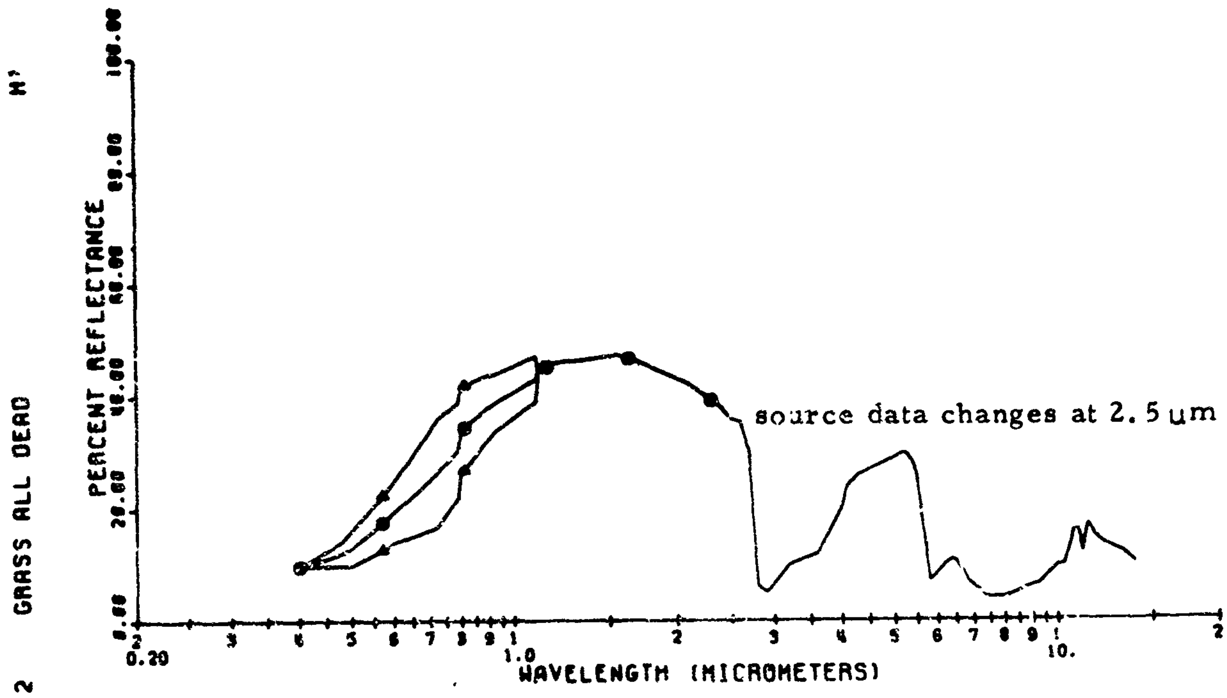


Figure 264. Spectral Reflectance of Dead Grasses

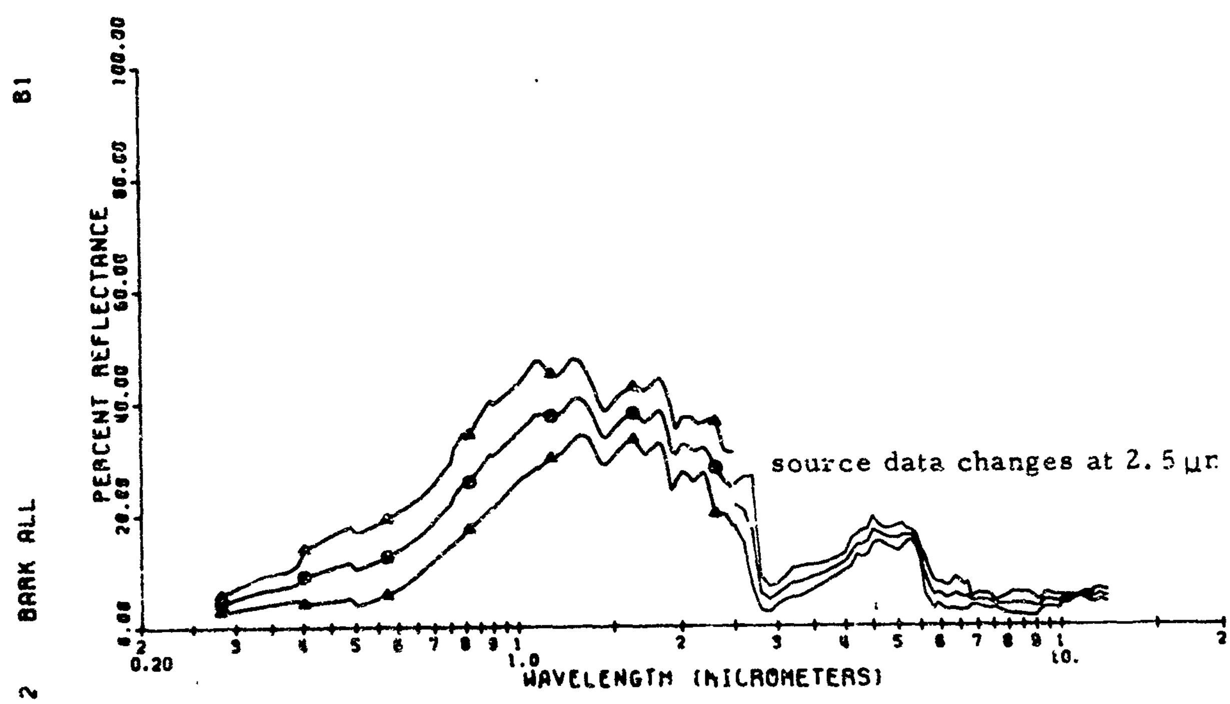


Figure 265. Spectral Reflectance of Bark

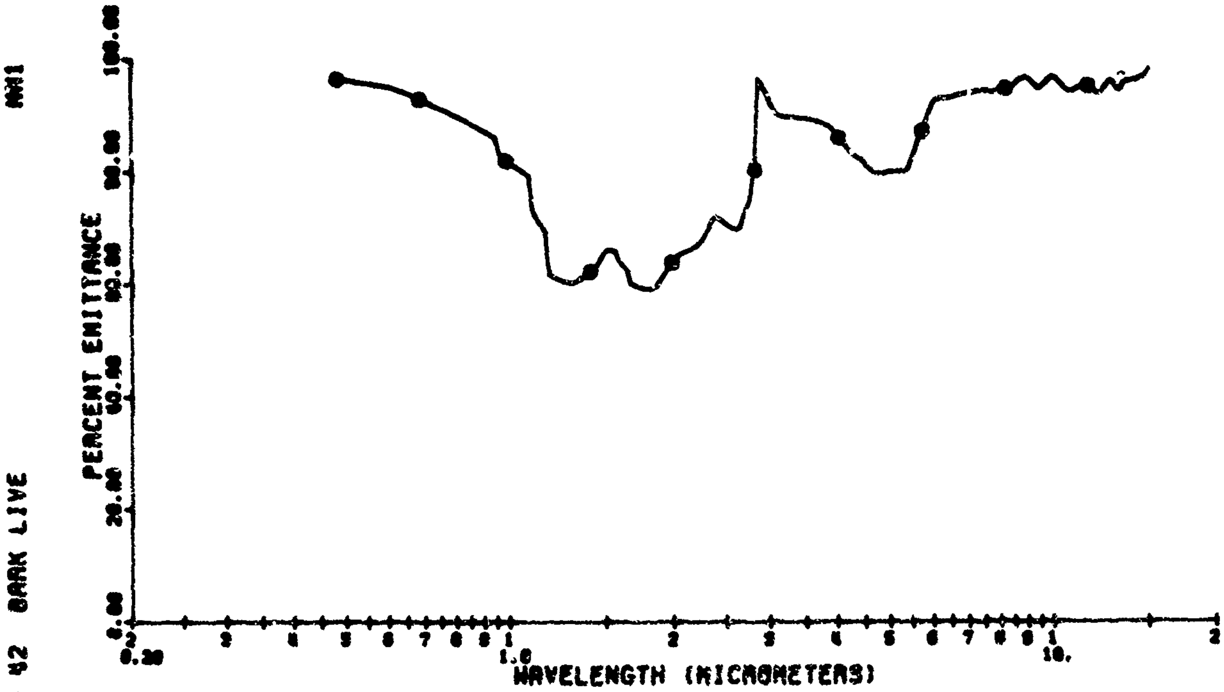


Figure 266. Spectral Emittance of Bark

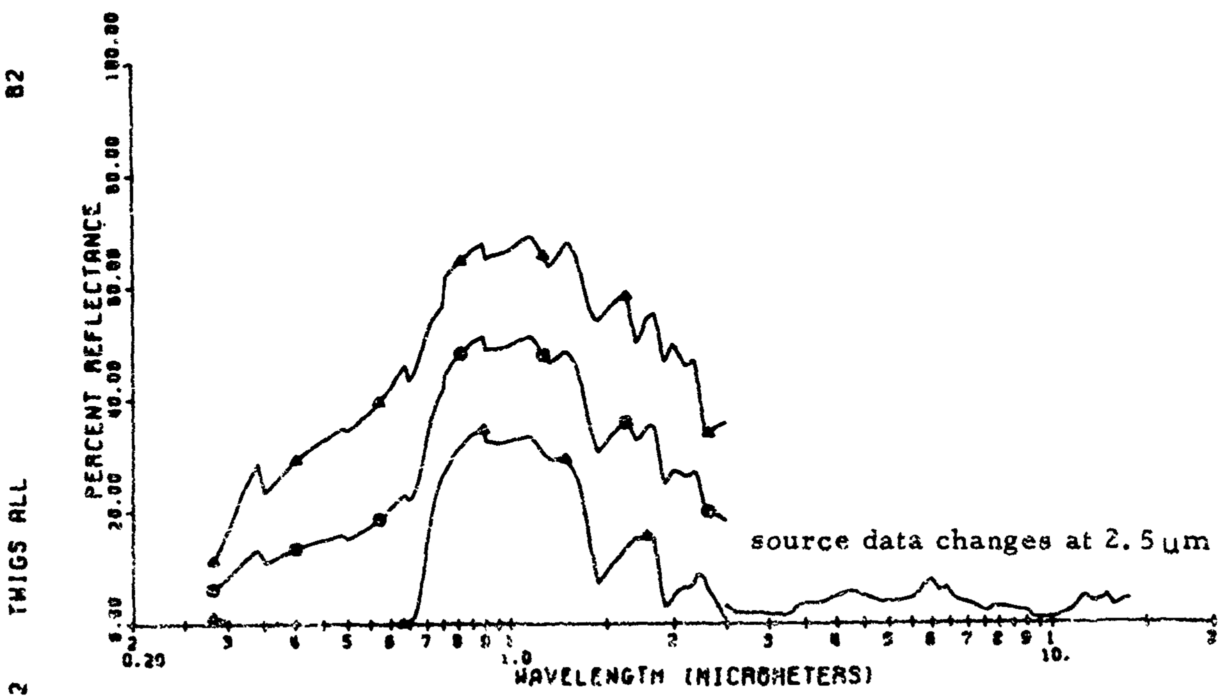


Figure 267. Spectral Reflectance of Twigs

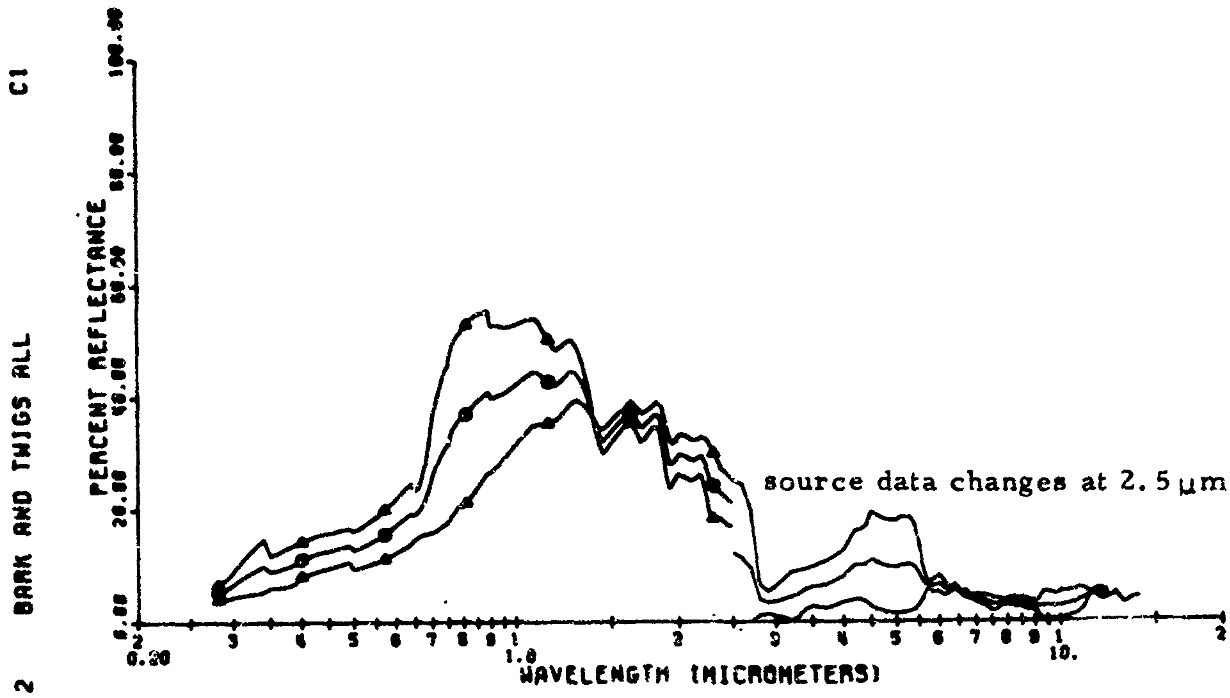


Figure 268. Spectral Reflectance of Bark and Twigs

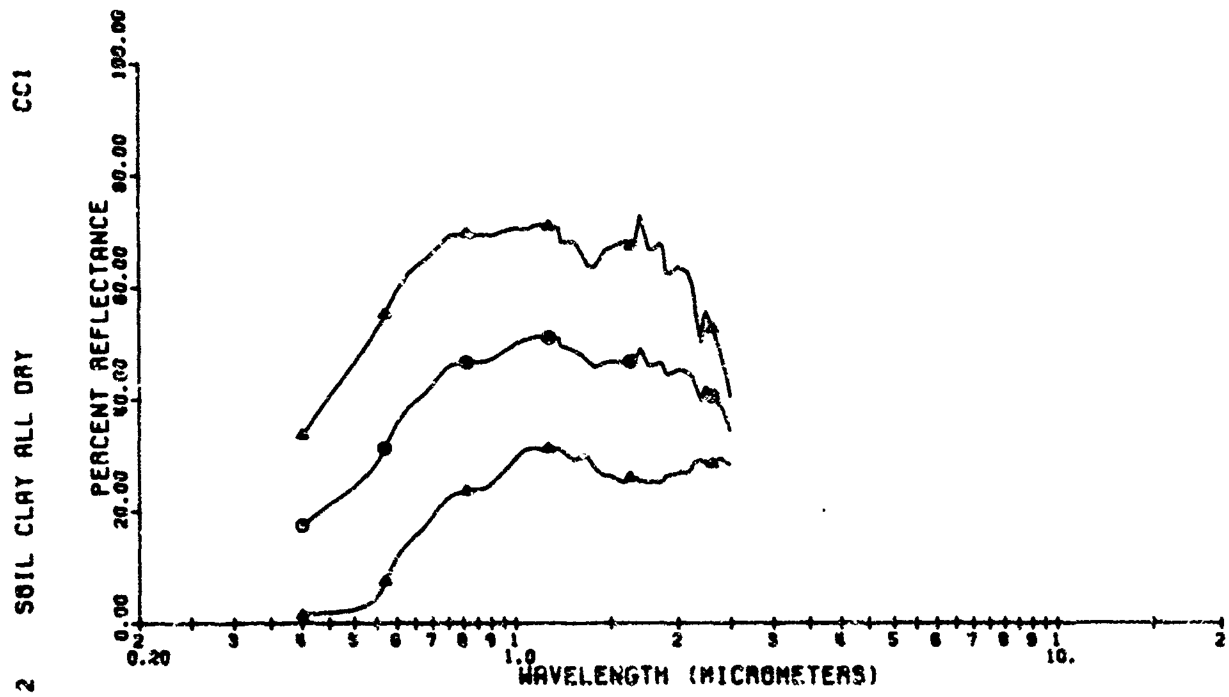


Figure 269. Spectral Reflectance of Dry Clay

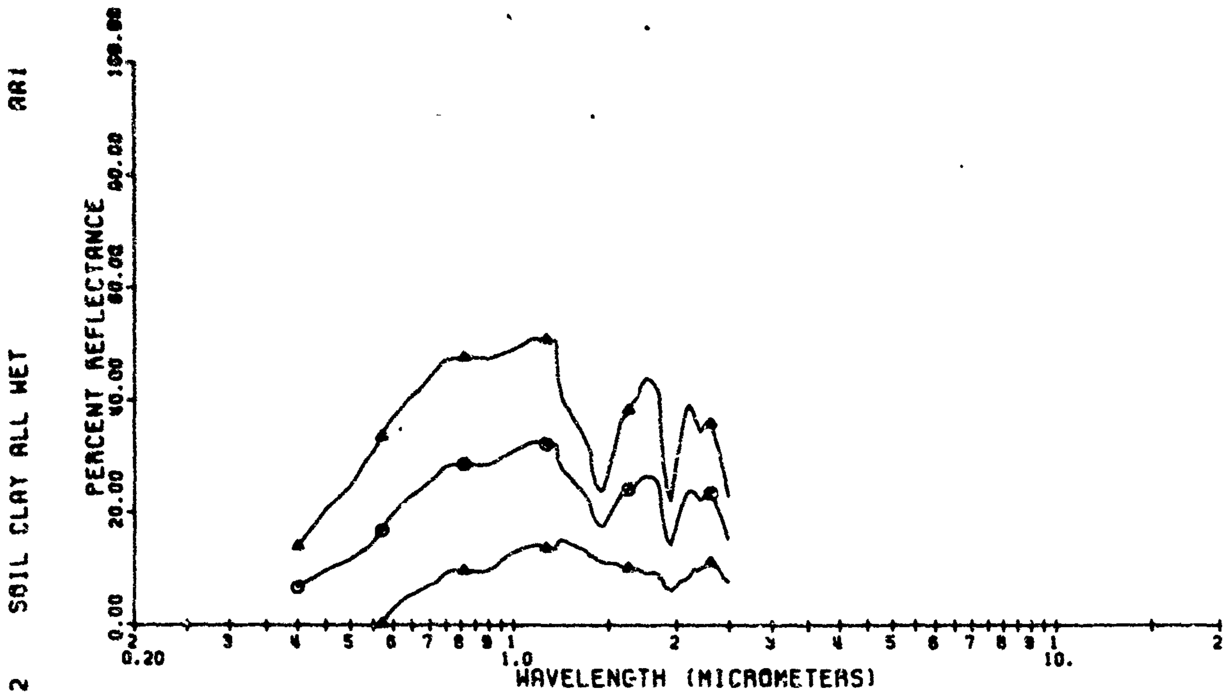


Figure 270. Spectral Reflectance of Wet Clay

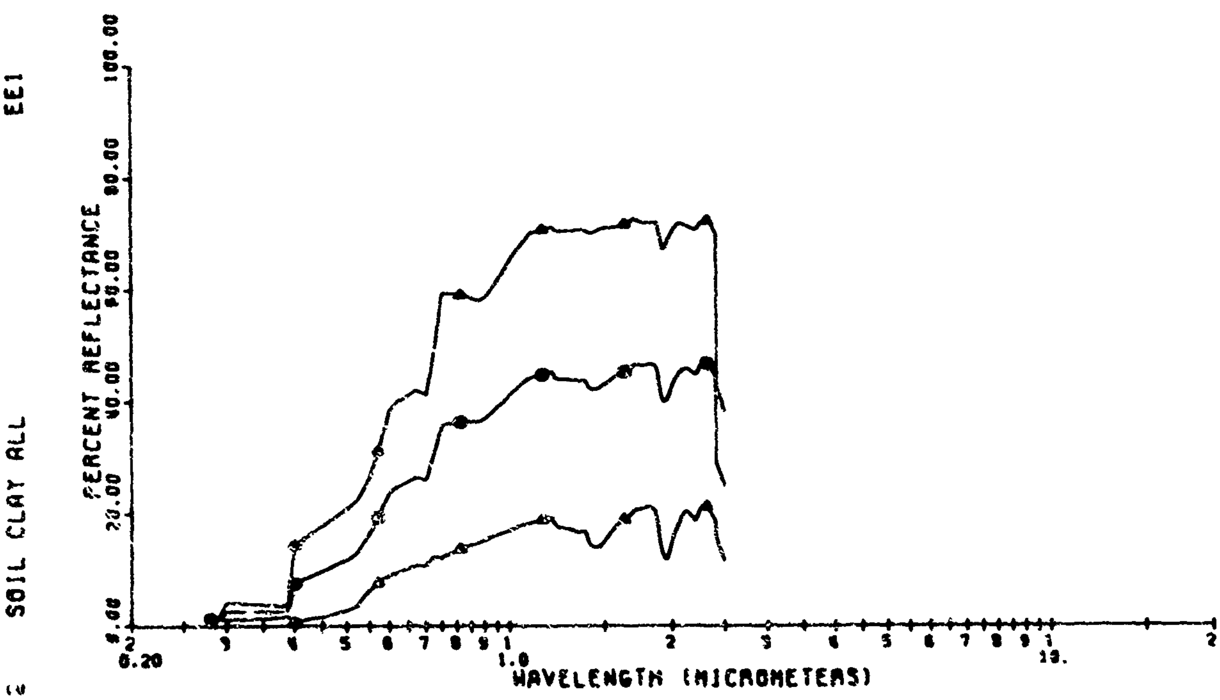


Figure 271. Spectral Reflectance of All Clay

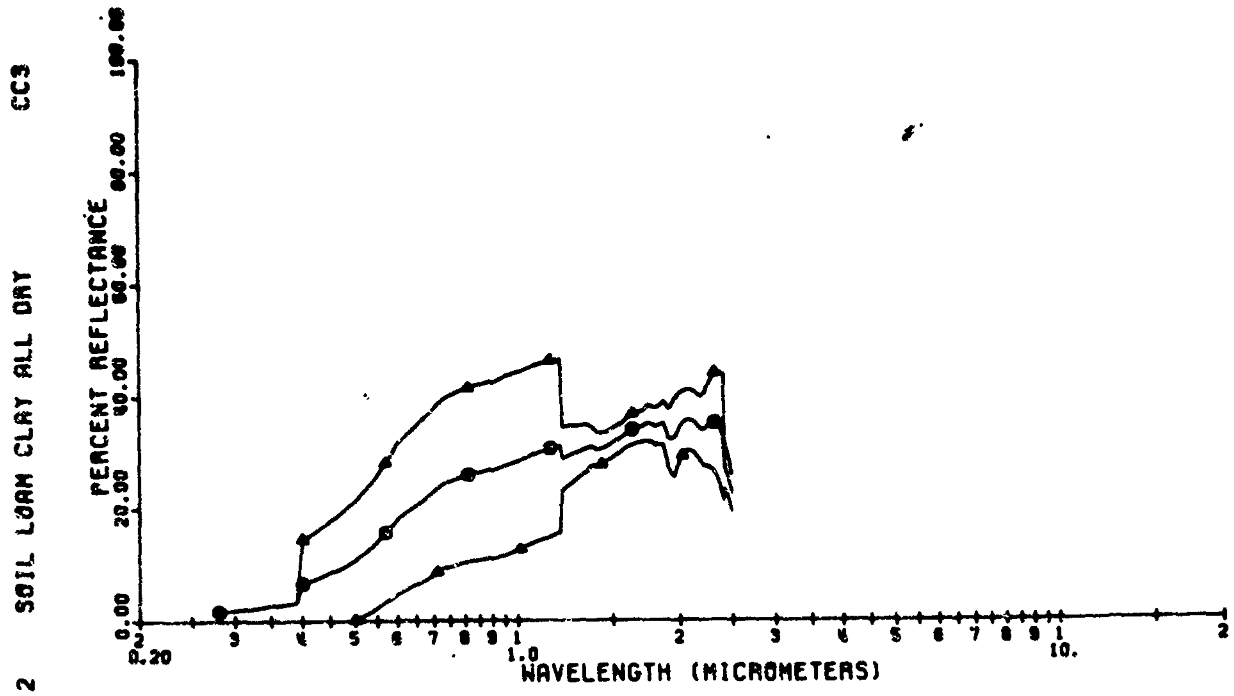


Figure 272. Spectral Reflectance of Dry Loam Clay

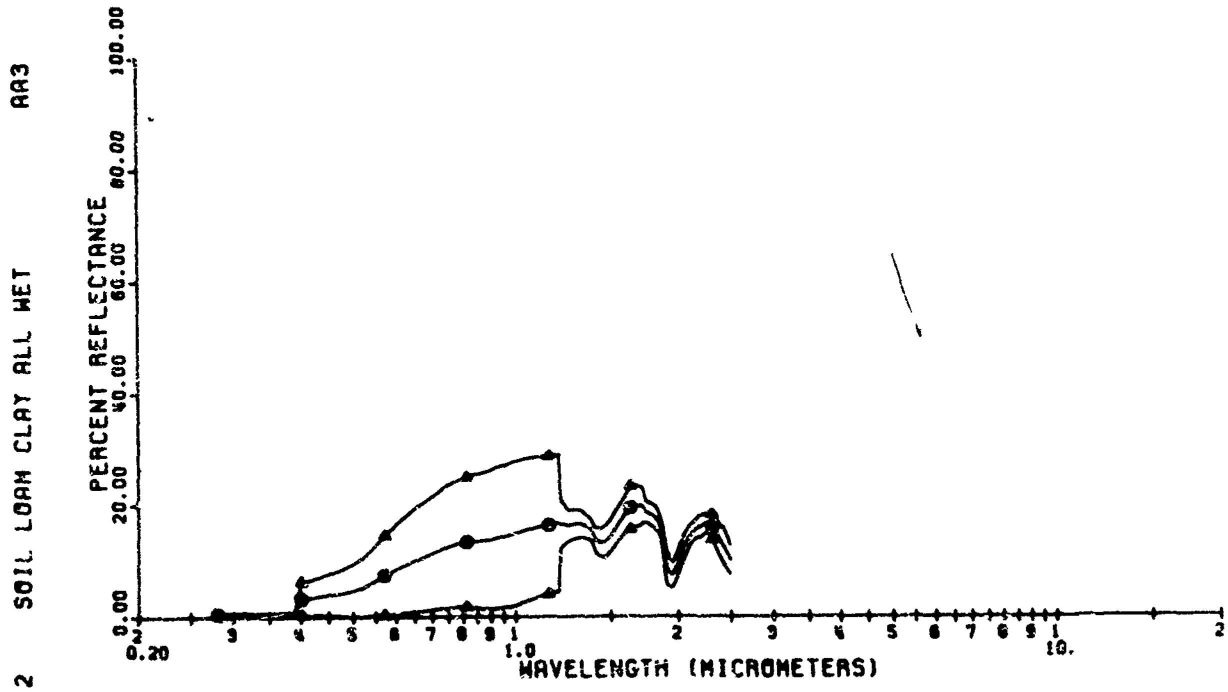


Figure 273. Spectral Reflectance of Wet Loam Clay

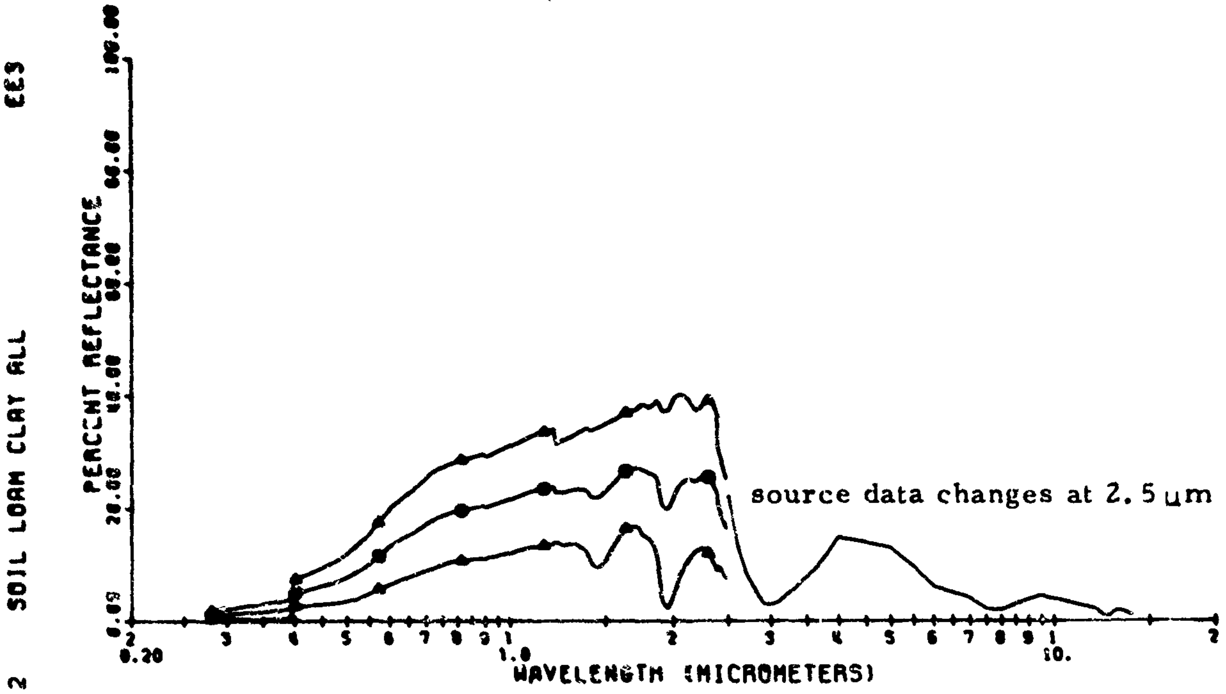


Figure 274. Spectral Reflectance of All Loam Clay

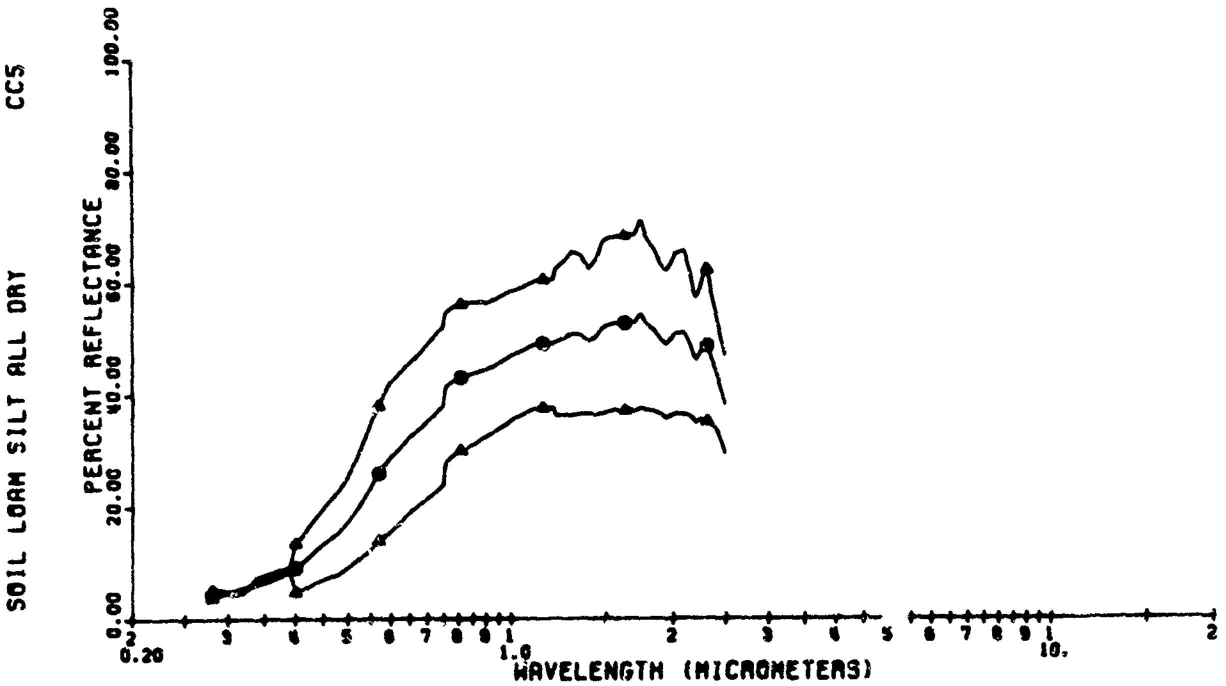


Figure 275. Spectral Reflectance of Dry Loam Silt

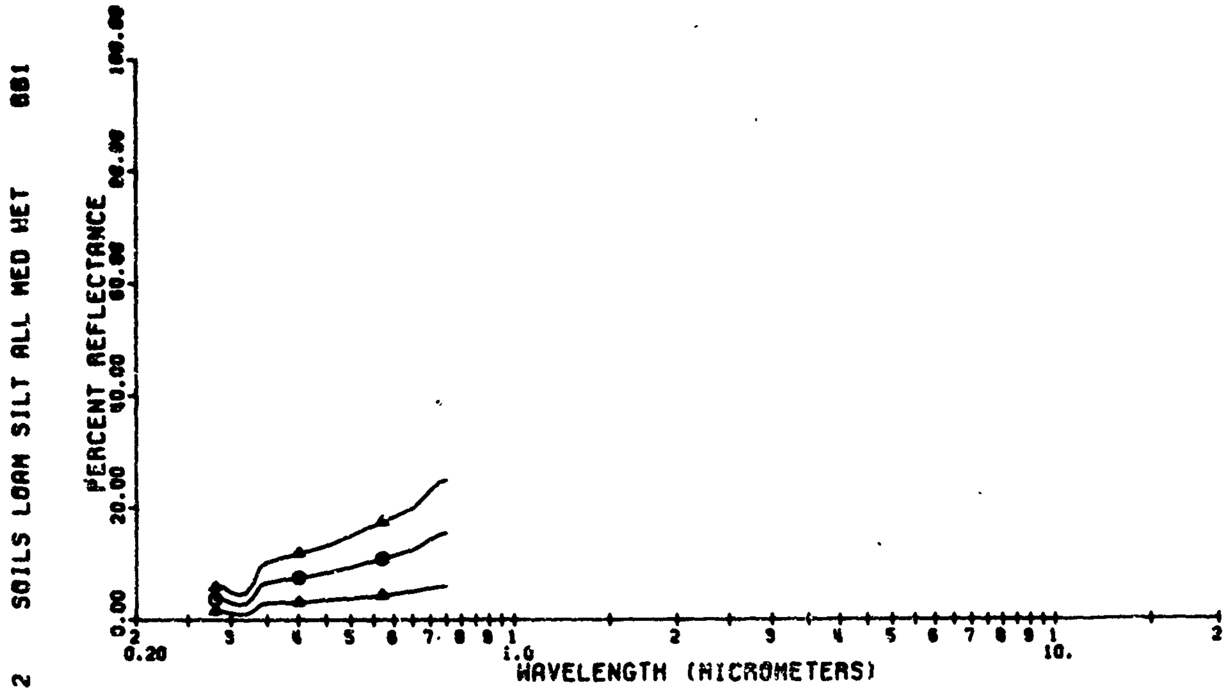


Figure 276. Spectral Reflectance of Medium Wet Loam Silt

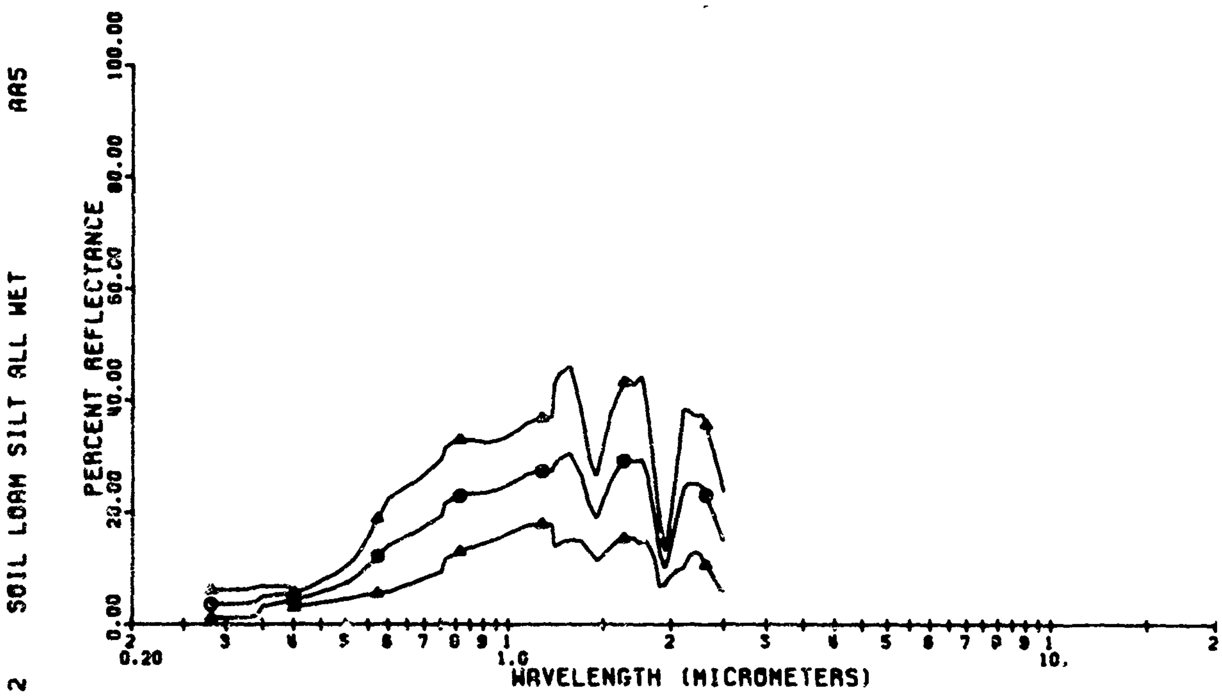


Figure 277. Spectral Reflectance of Wet Loam Silt

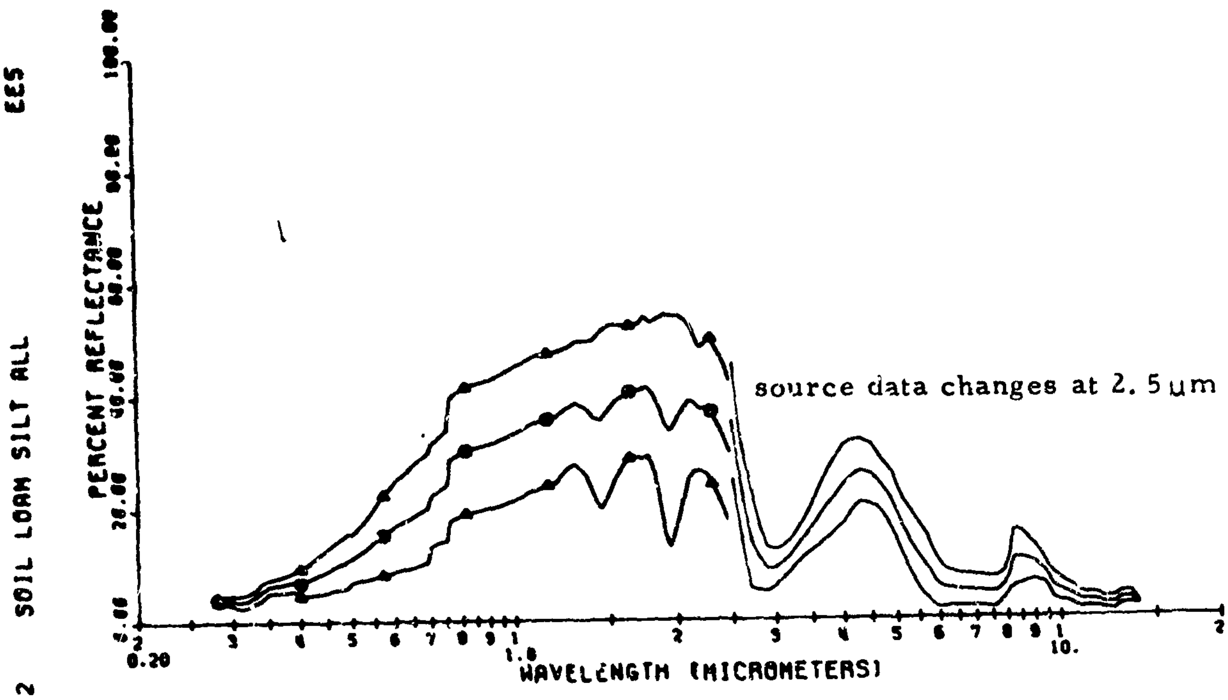


Figure 278. Spectral Reflectance of All Loam Silt

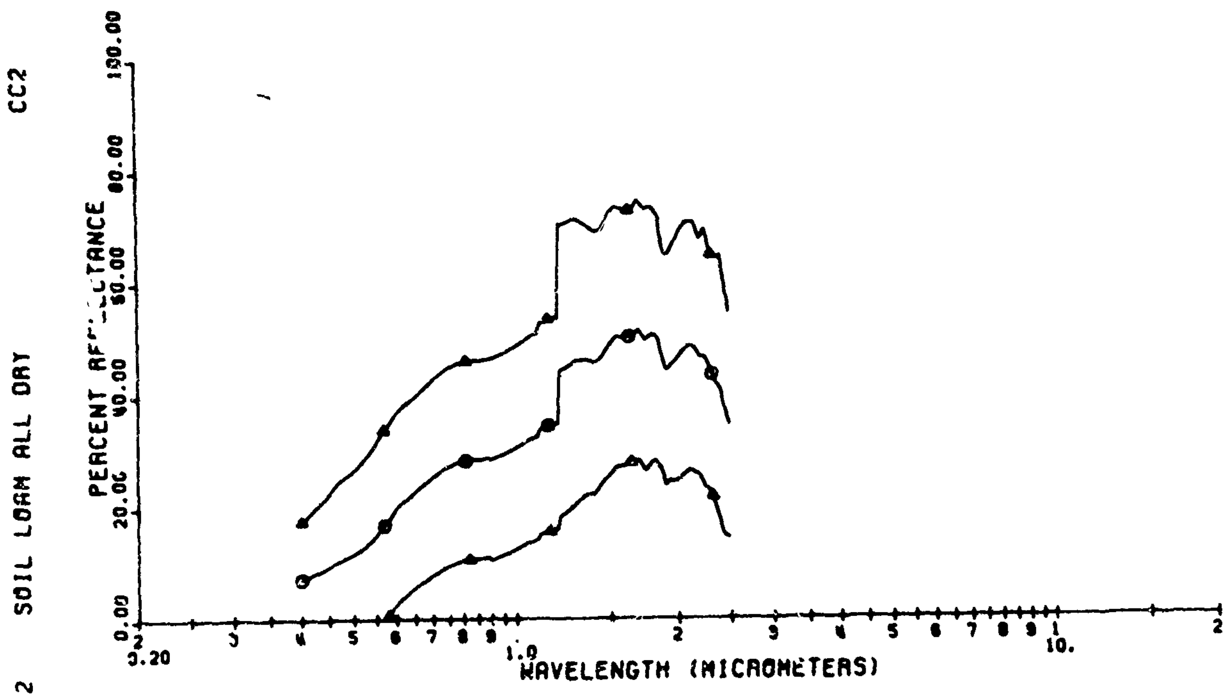


Figure 279. Spectral Reflectance of Dry Loam

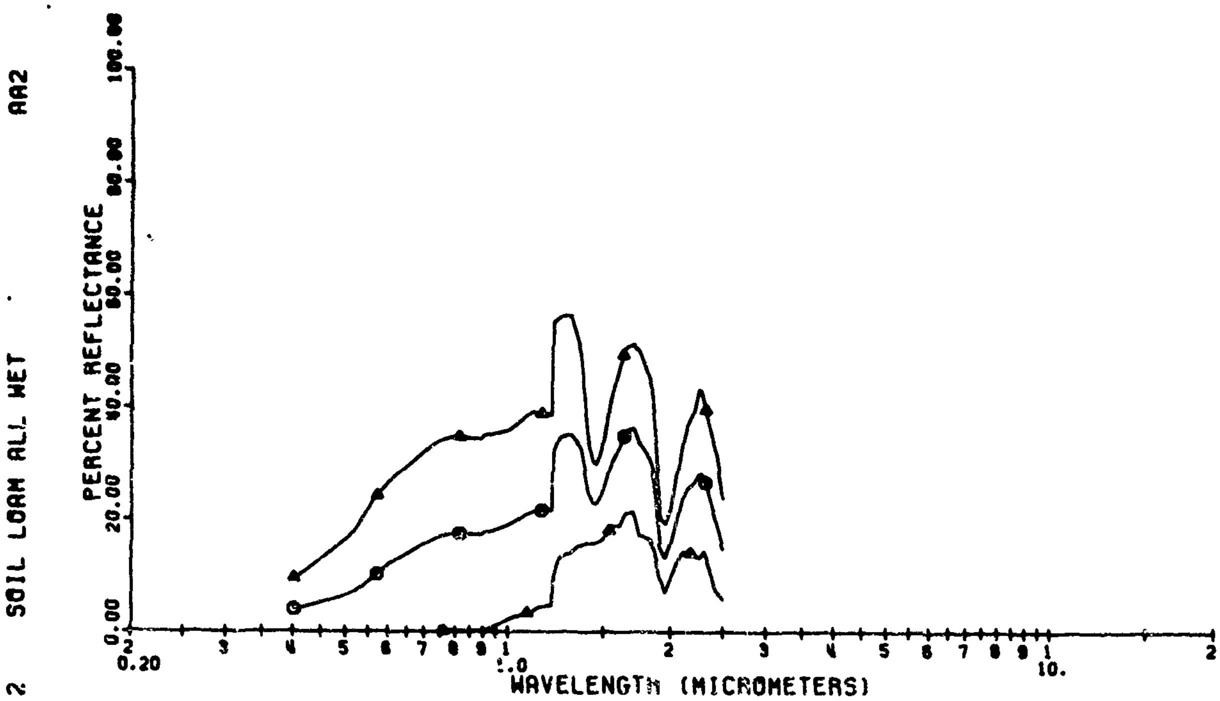


Figure 280. Spectral Reflectance of Wet Loam

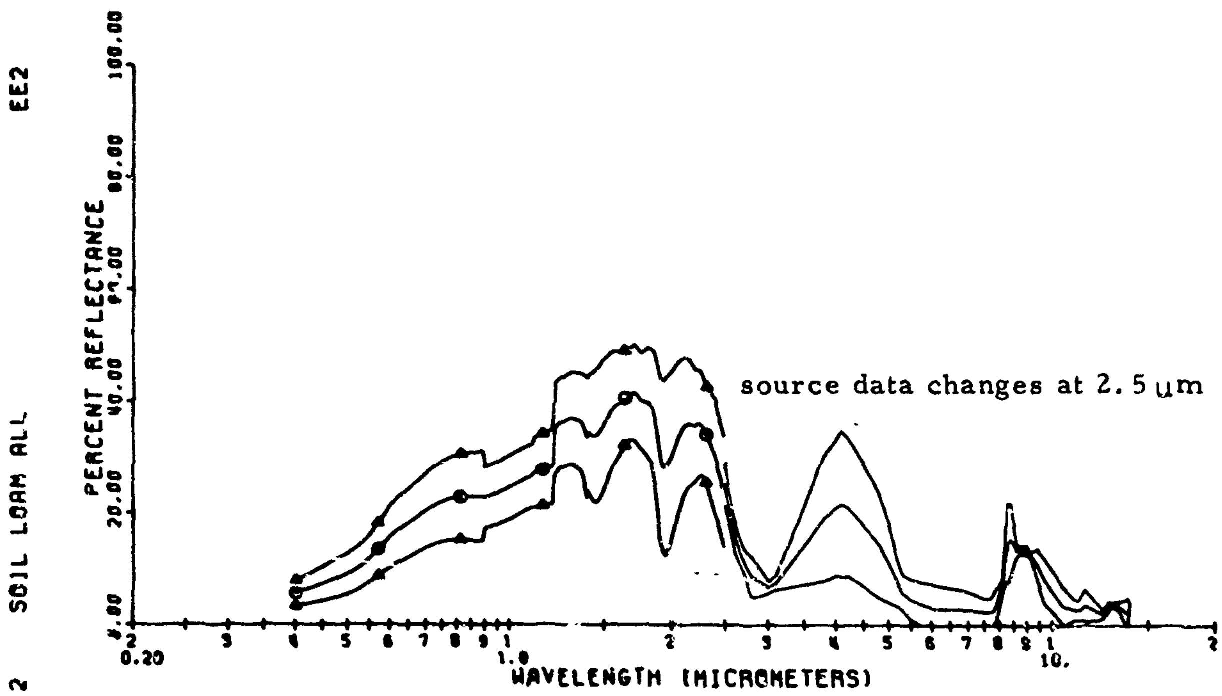


Figure 281. Spectral Reflectance of All Loam

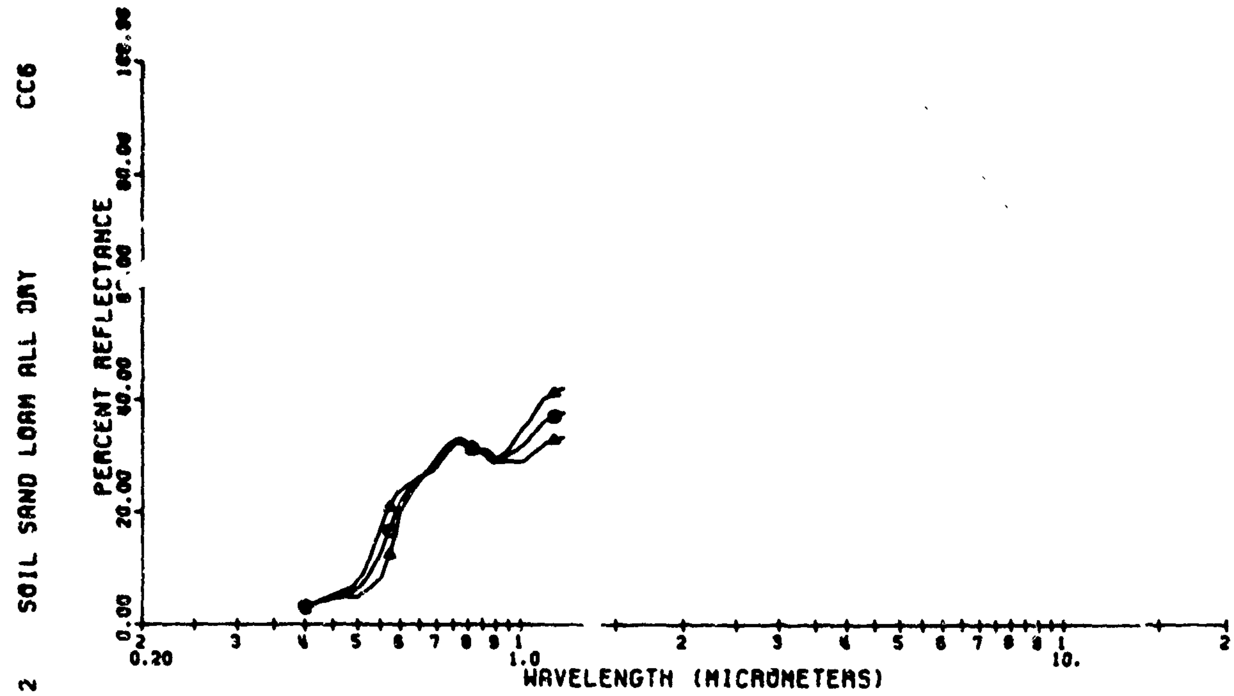


Figure 282. Spectral Reflectance of Dry Sandy Loam

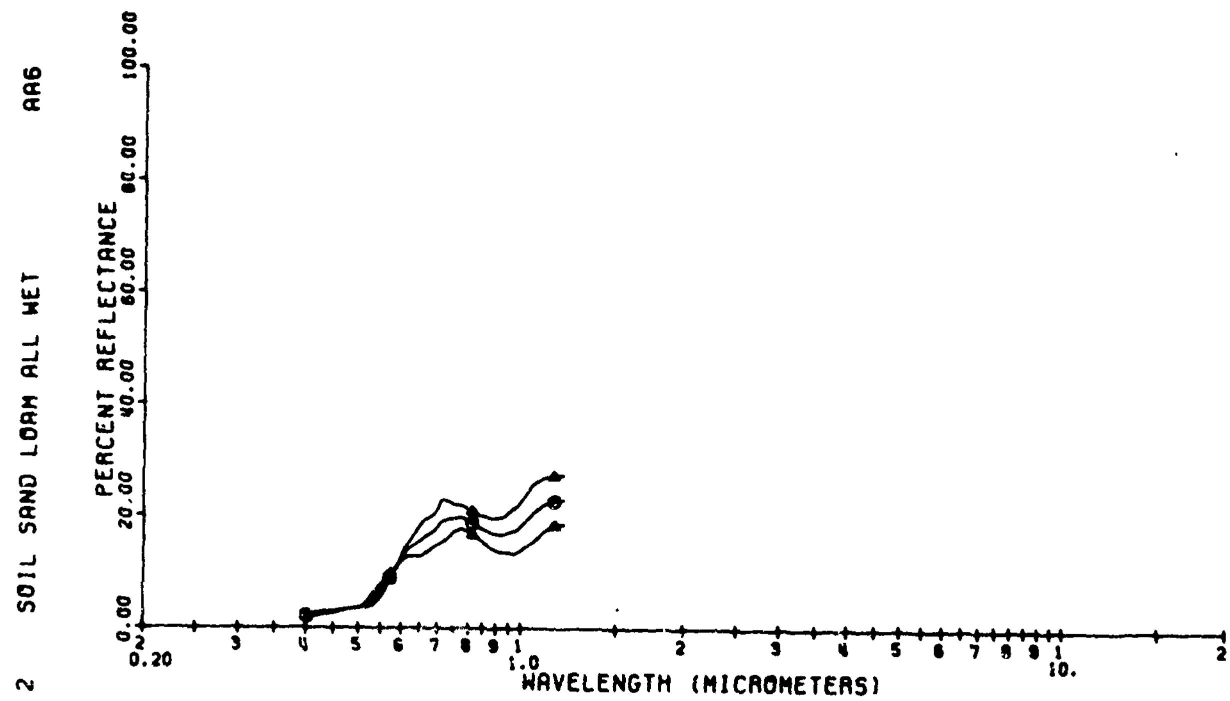


Figure 283. Spectral Reflectance of Wet Sandy Loam

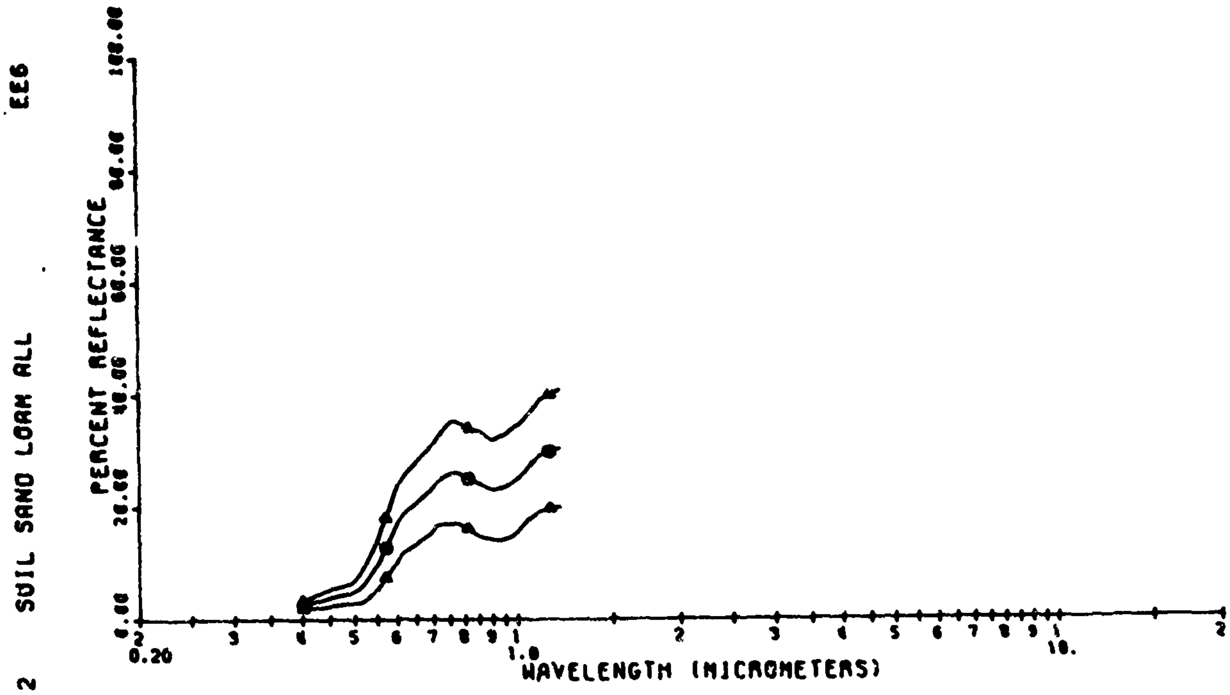


Figure 284. Spectral Reflectance of All Sandy Loam

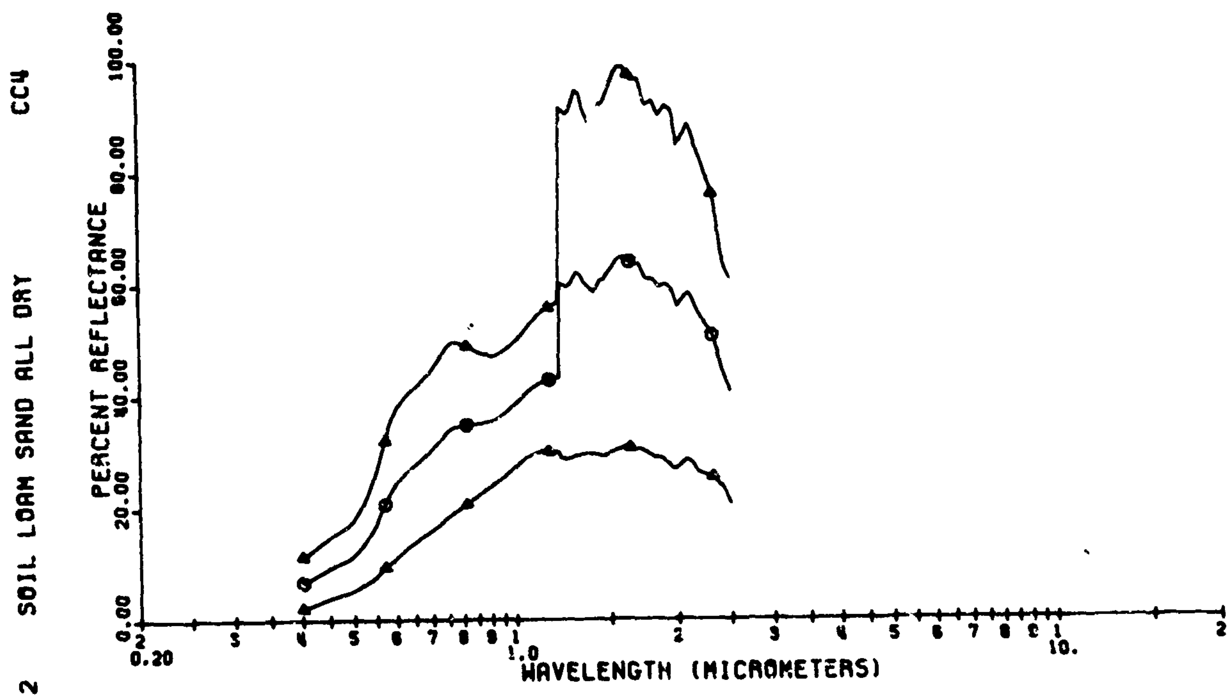


Figure 285. Spectral Reflectance of Dry Loamy Sand

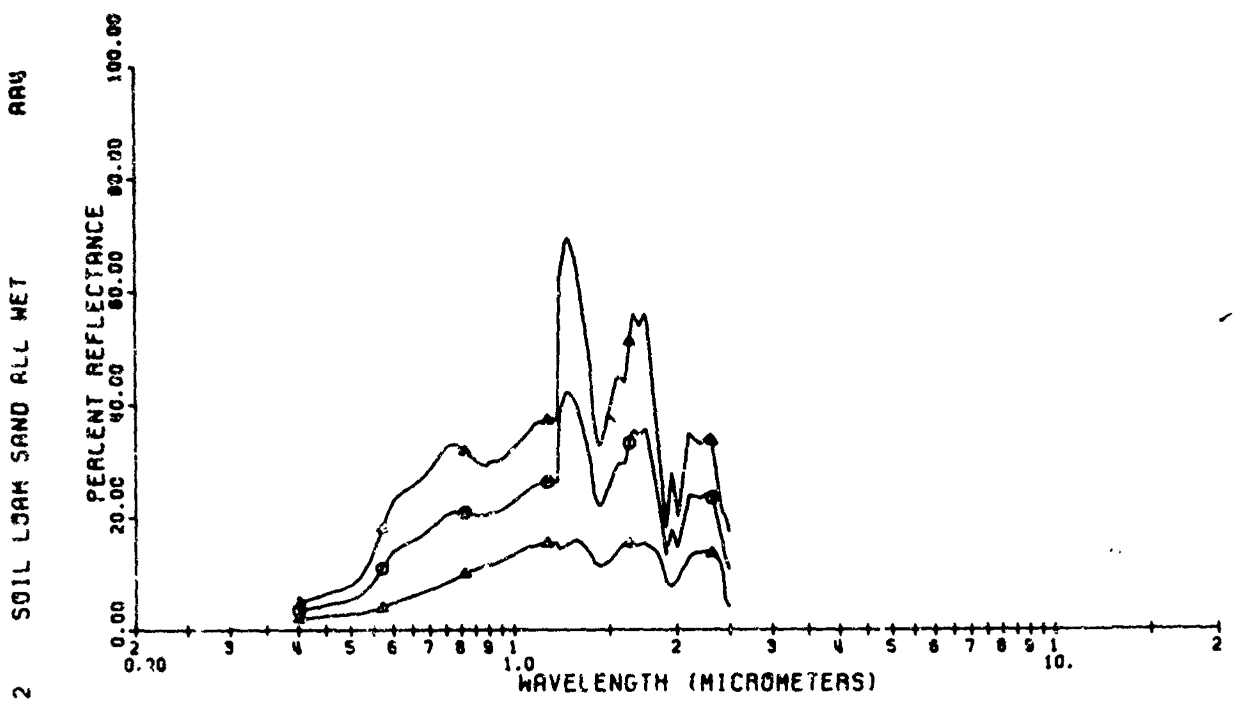


Figure 286. Spectral Reflectance of Wet Loamy Sand

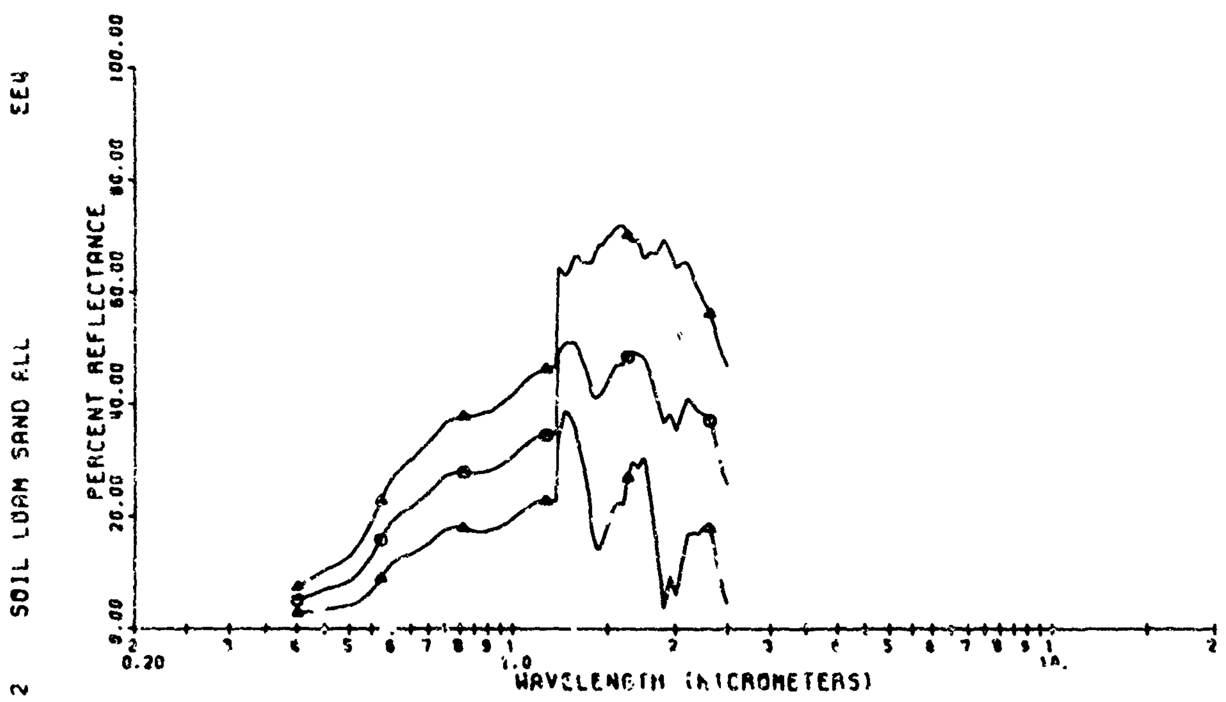


Figure 287. Spectral Reflectance of All Loamy Sand

SOIL SAND ALL DRY 2 CC7

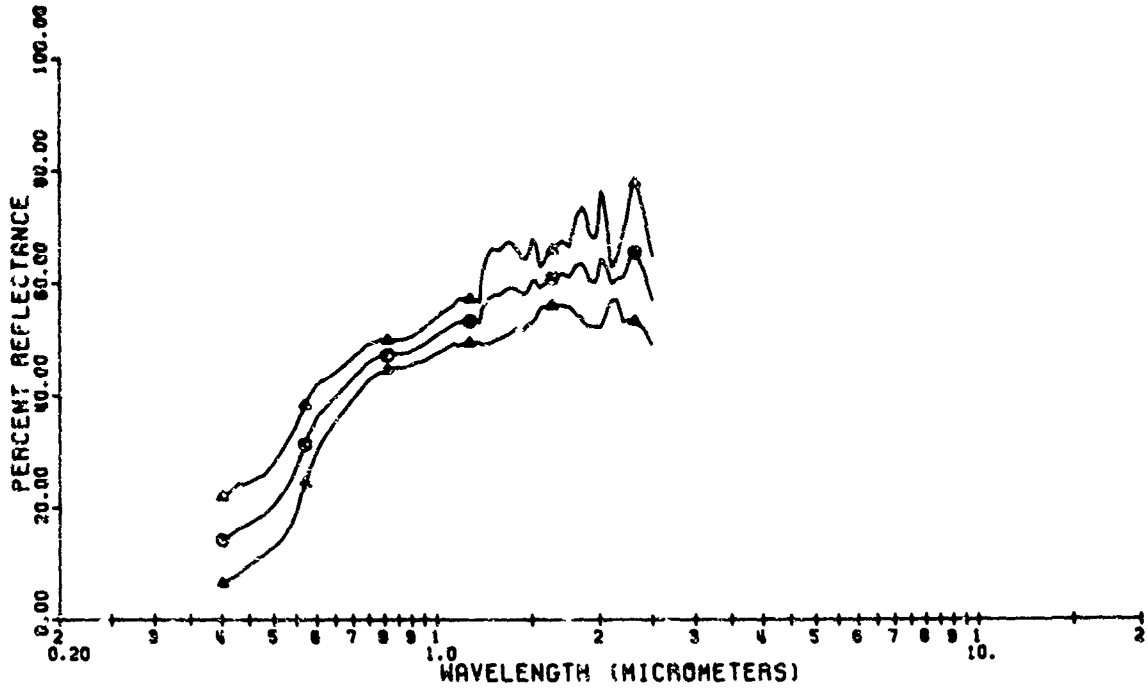


Figure 288. Spectral Reflectance of Dry Sand

FIG 31 SAND NM2

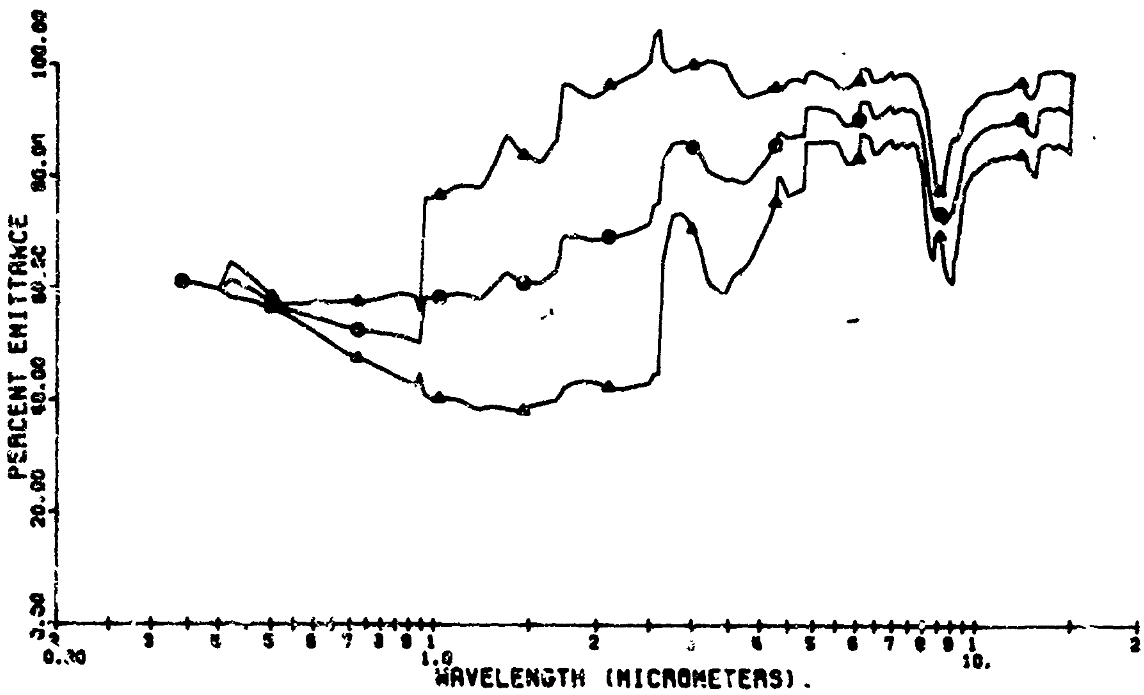


Figure 289. Spectral Emittance of Dry Sand

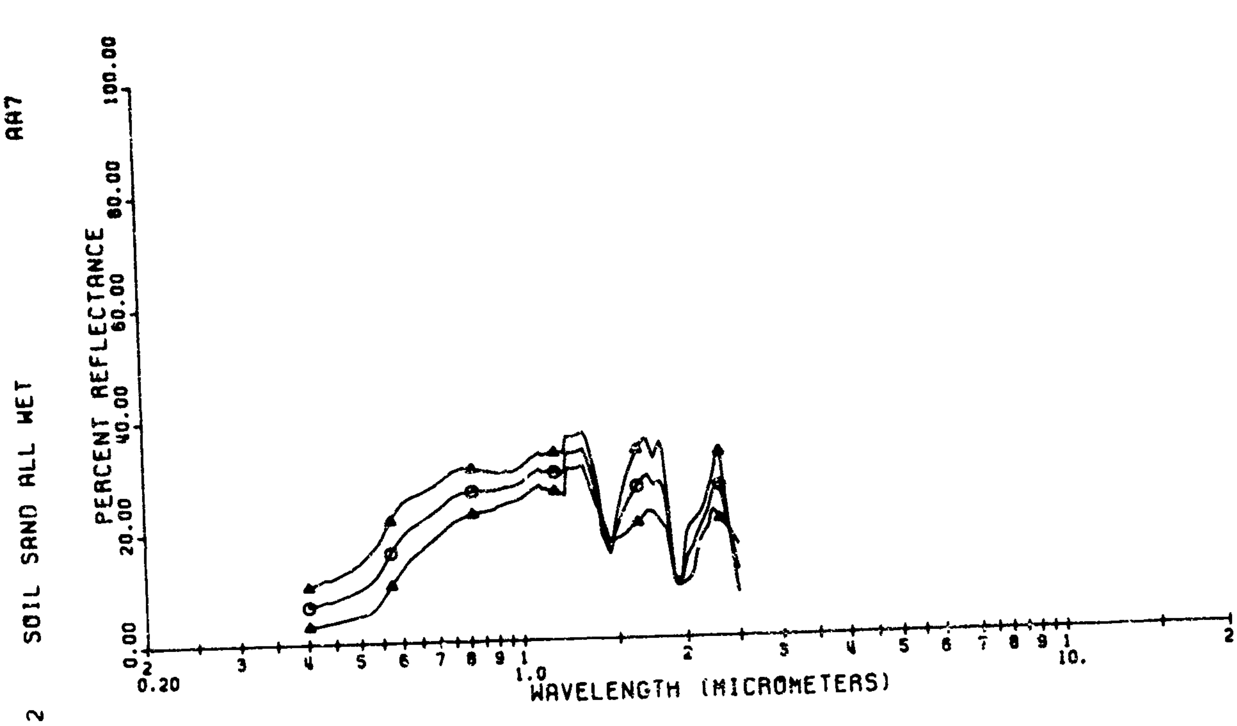


Figure 290. Spectral Reflectance of Wet Sa d

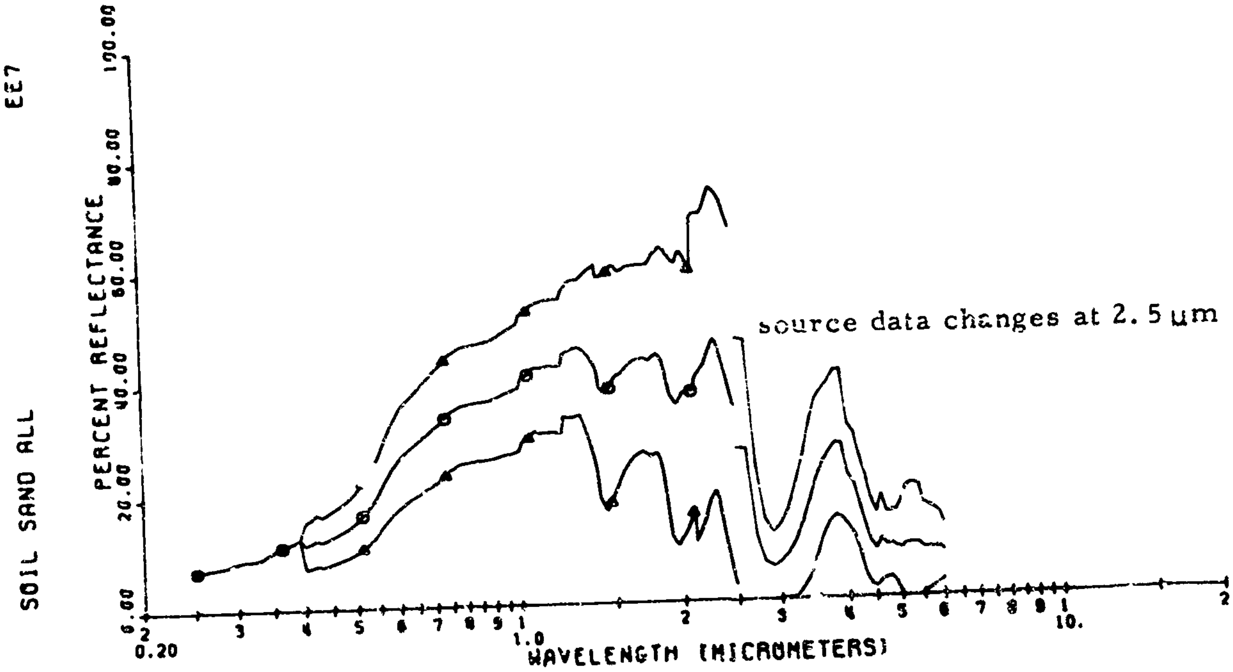


Figure 291. Spectral Reflectance of All Sand

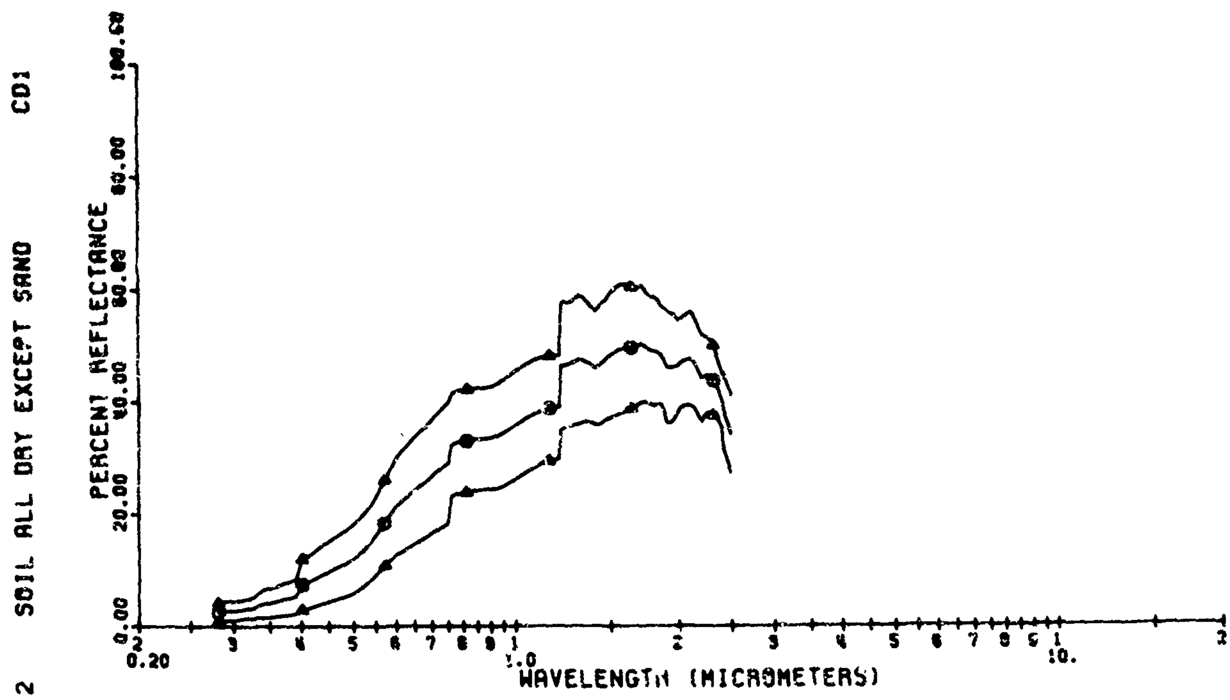


Figure 292. Spectral Reflectance of All Dry Soils Except Sand

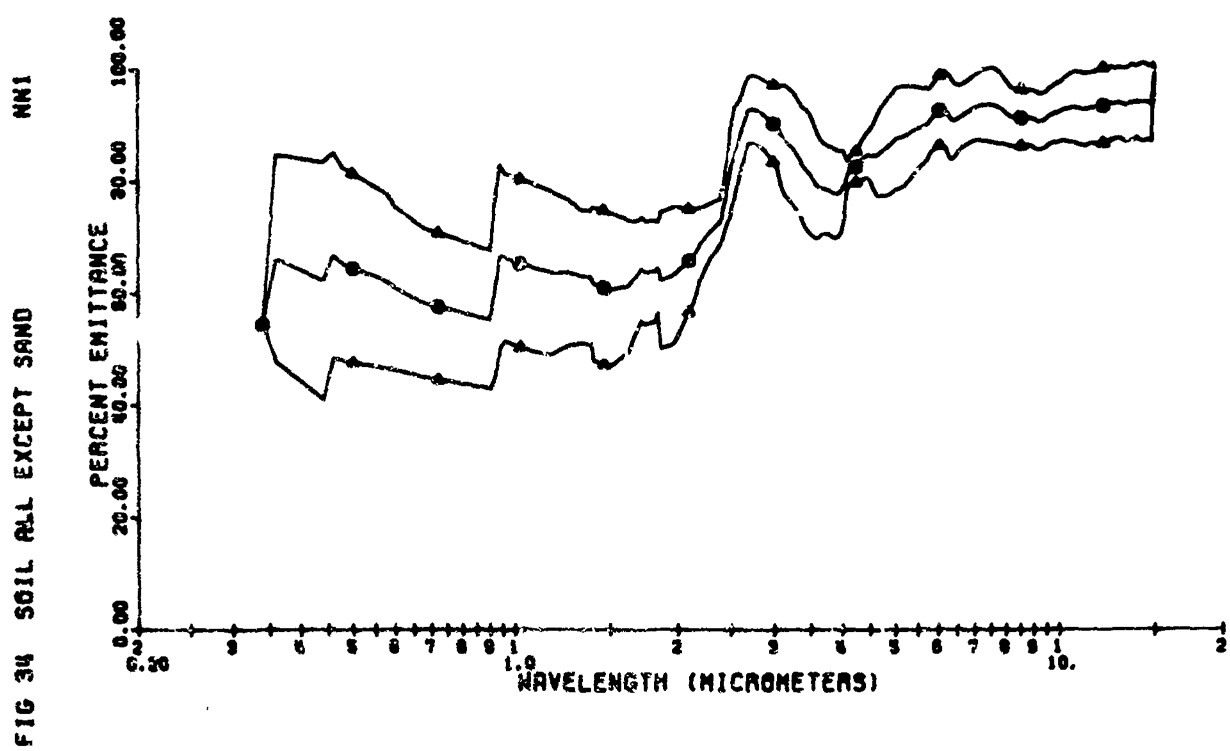


Figure 293. Spectral Emittance of All Dry Soils Except Sand

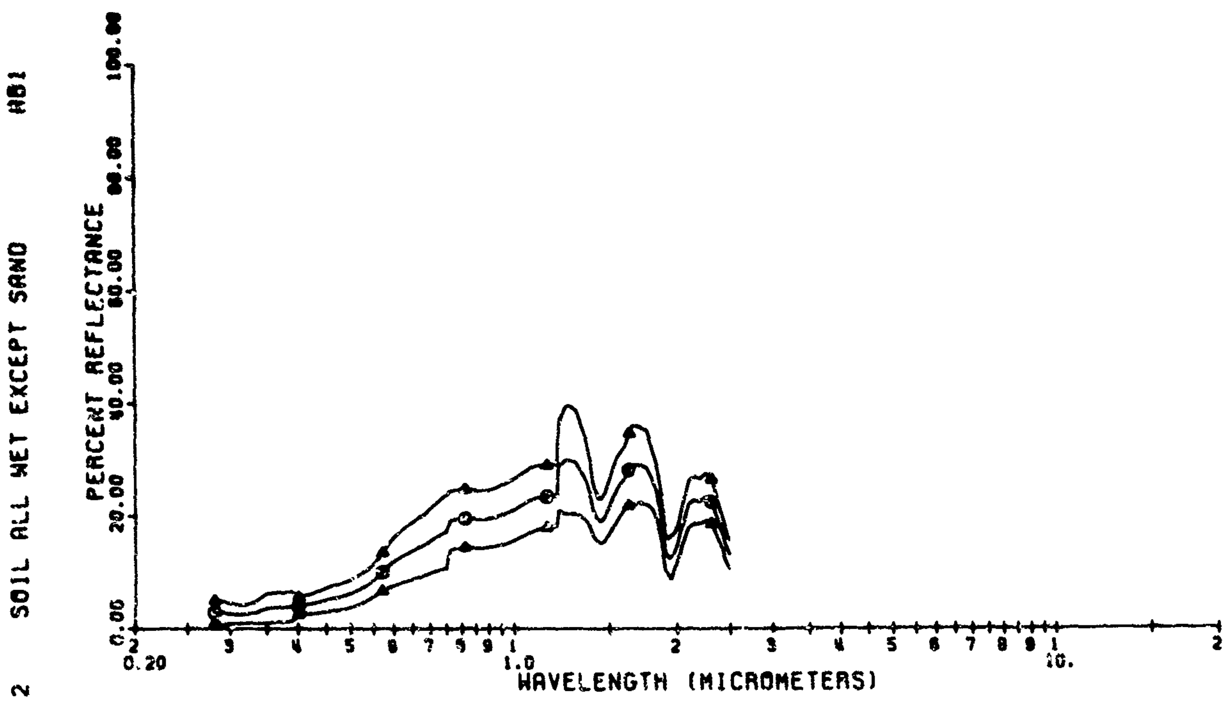


Figure 294. Spectral Reflectance of All Wet Soils Except Sand

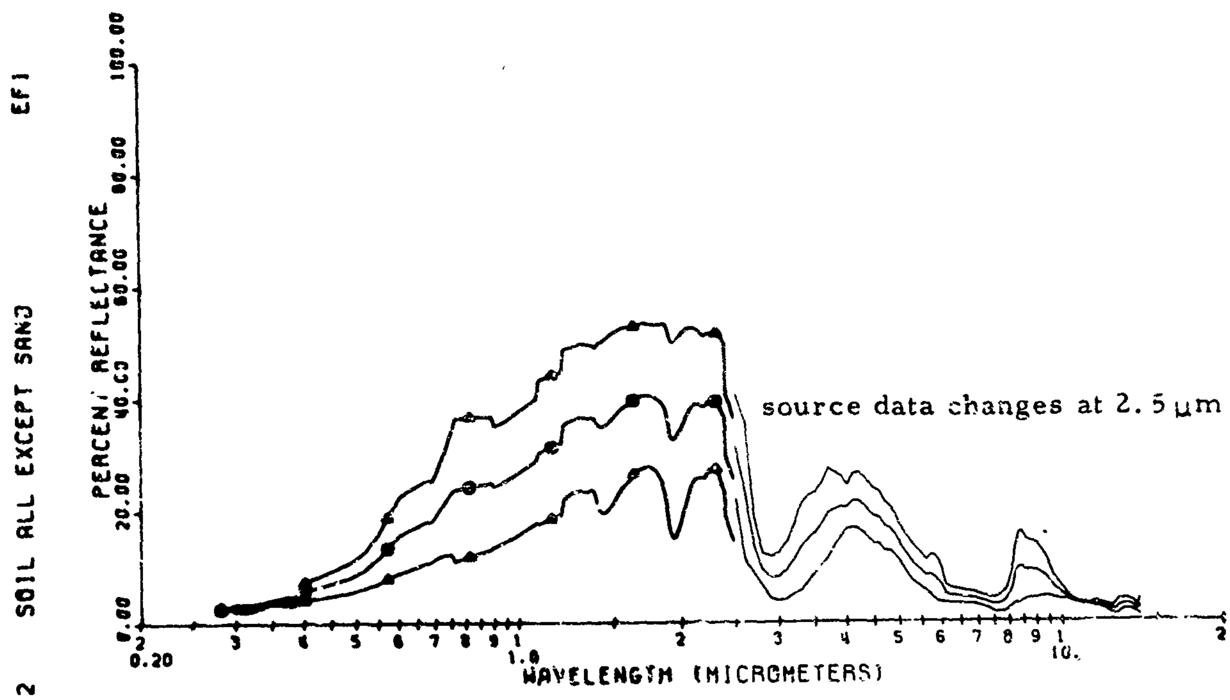


Figure 295. Spectral Reflectance of All Soils Except Sand

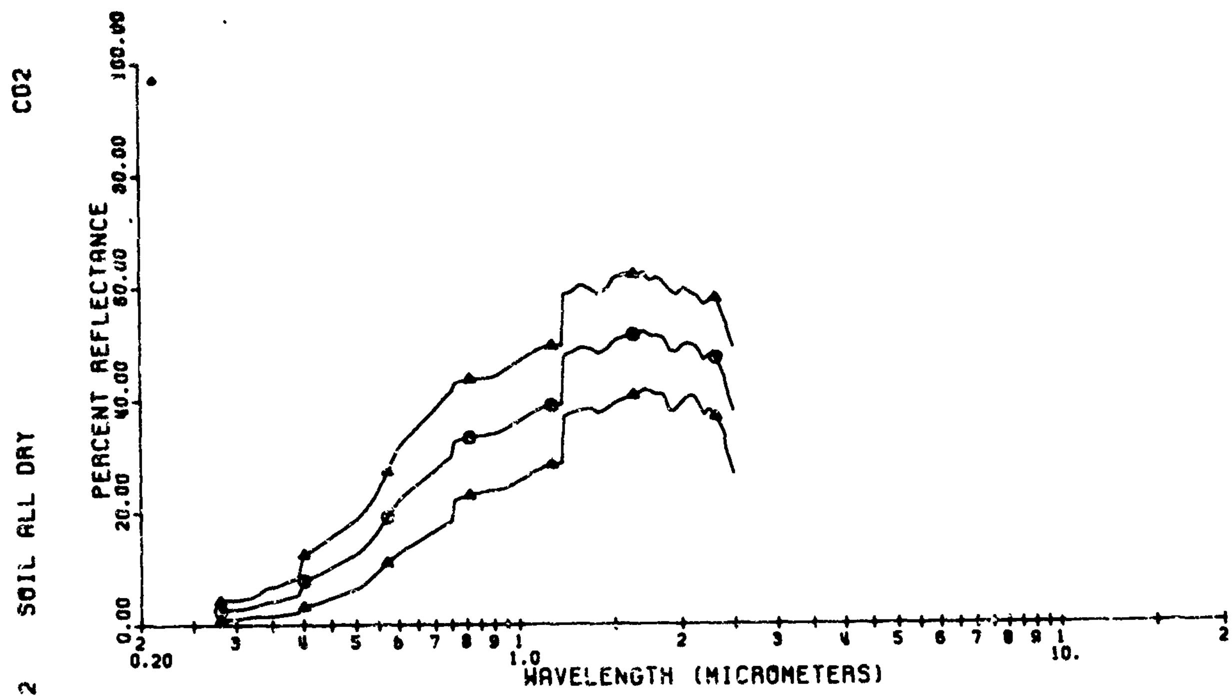


Figure 296. Spectral Reflectance of All Dry Soils Including Sand

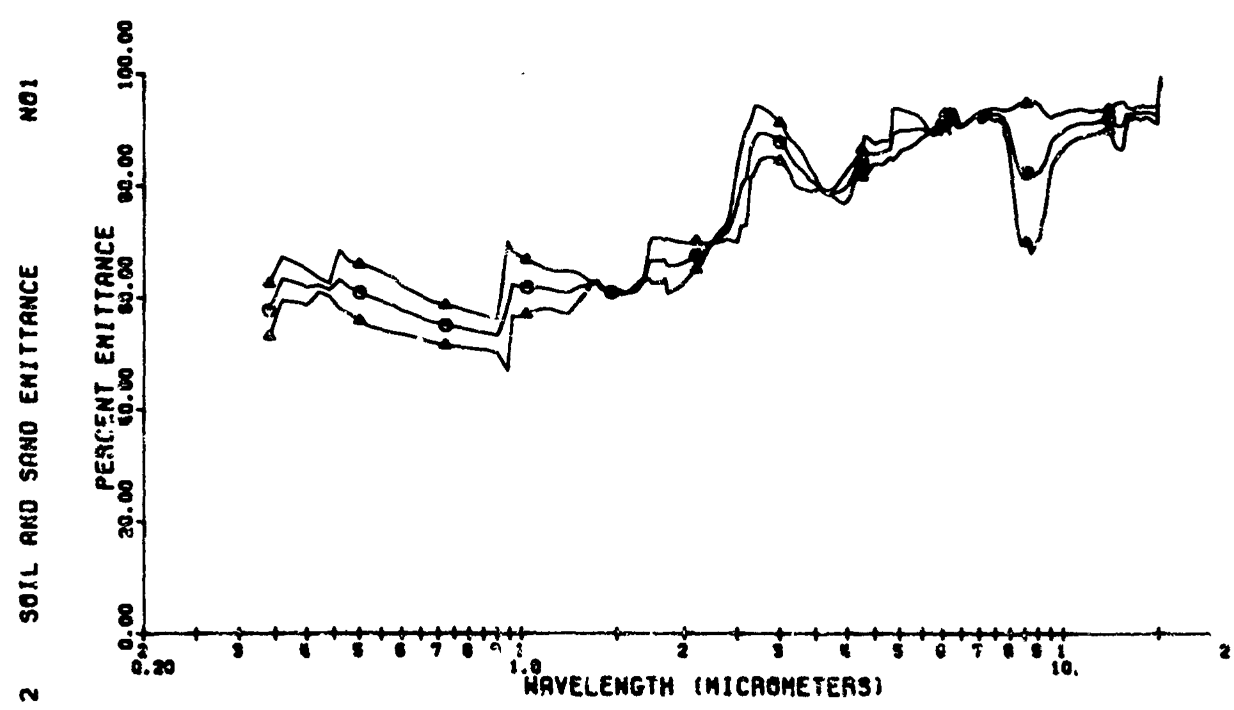


Figure 297. Spectral Emittance of All Dry Soils Including Sand

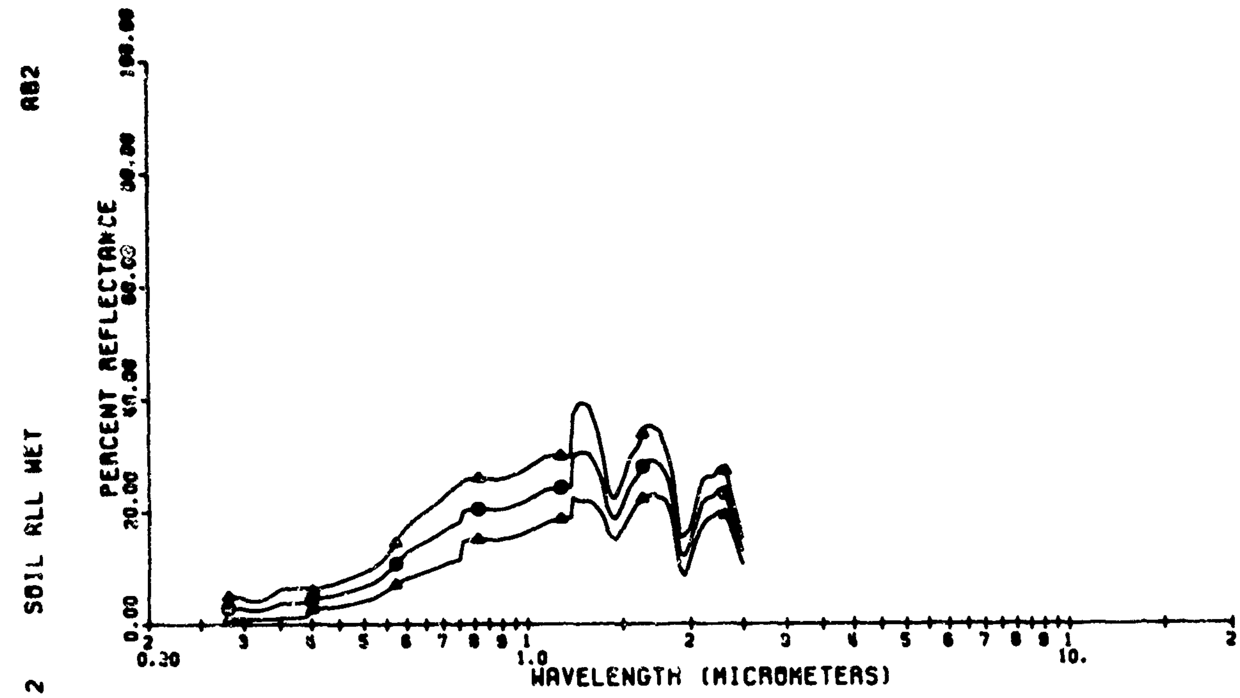


Figure 298. Spectral Reflectance of All Wet Soils Including Sand

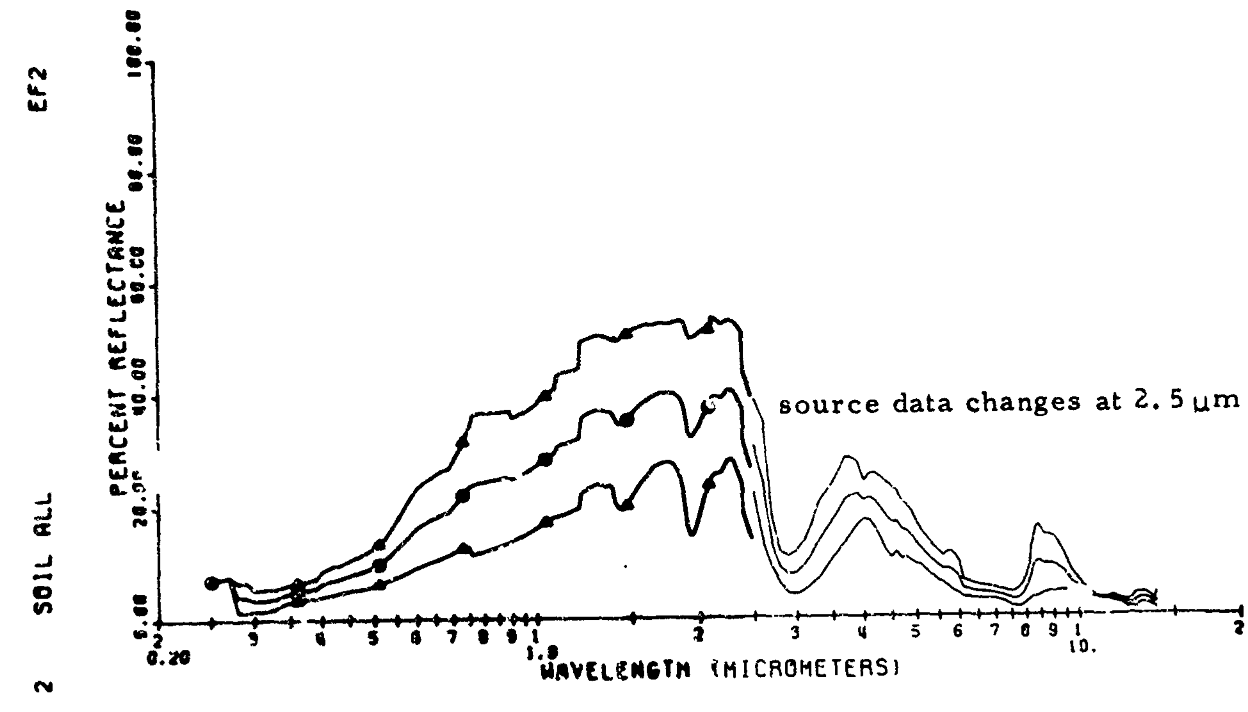


Figure 299. Spectral Reflectance of All Soils Including Sand

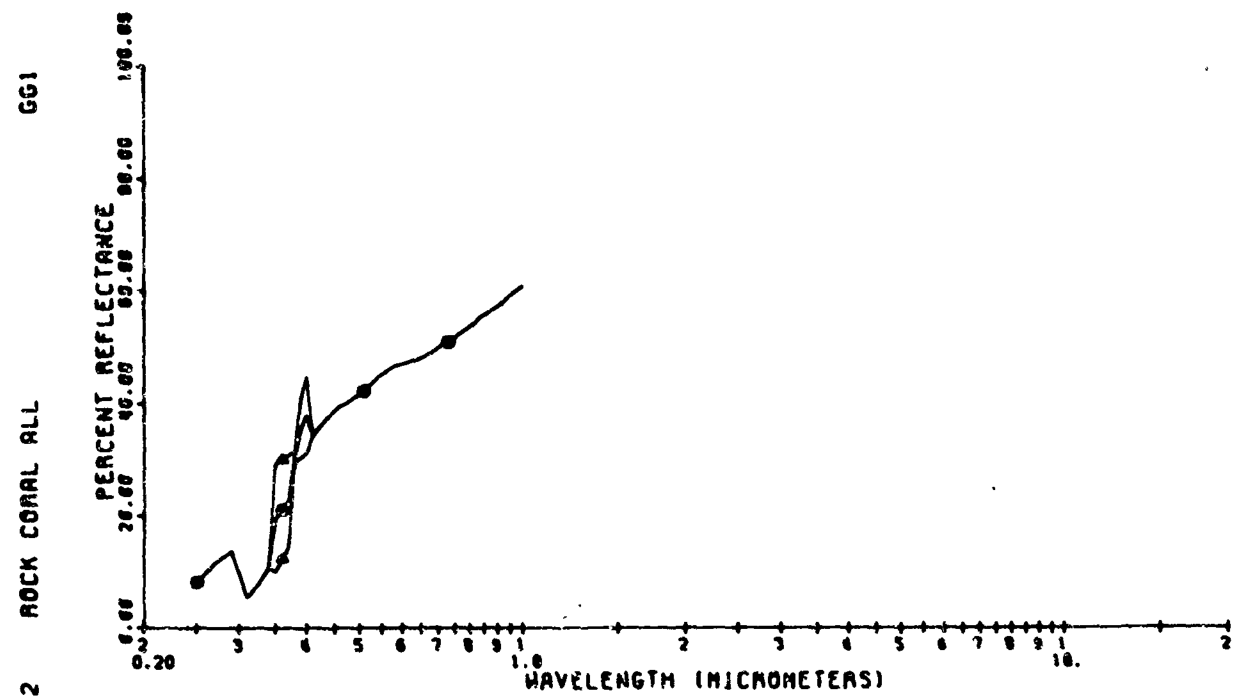


Figure 300. Spectral Reflectance of Coral

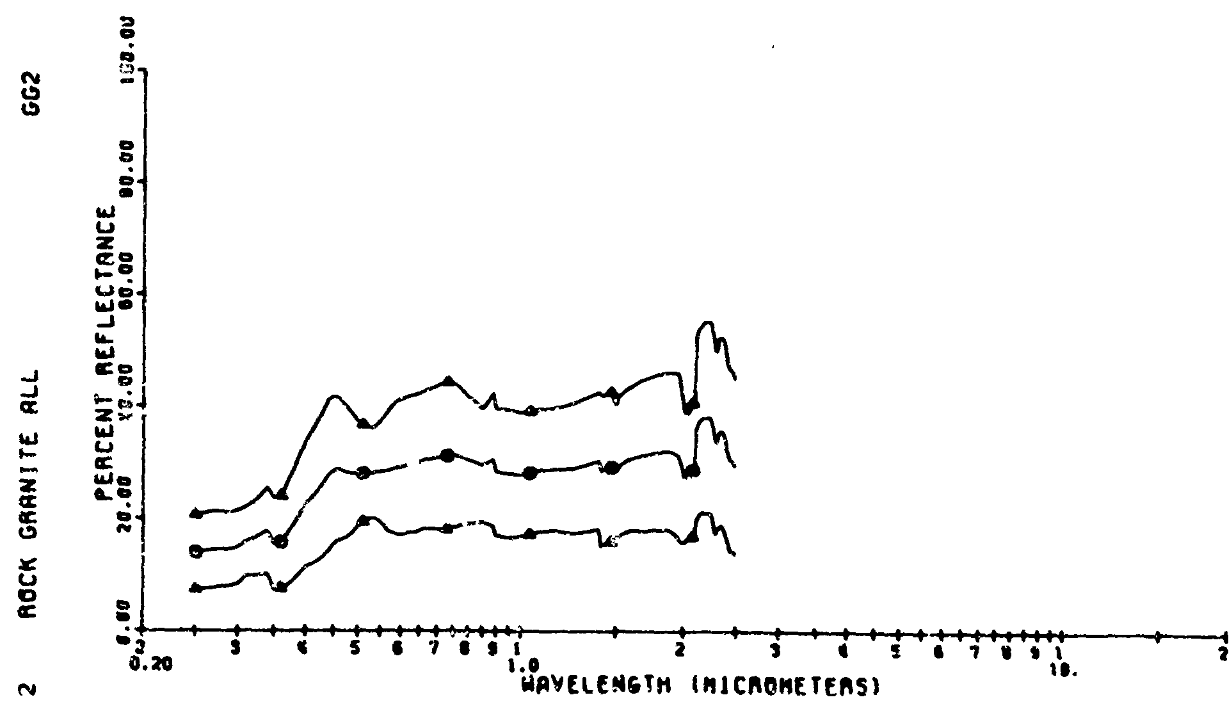


Figure 301. Spectral Reflectance of Granite

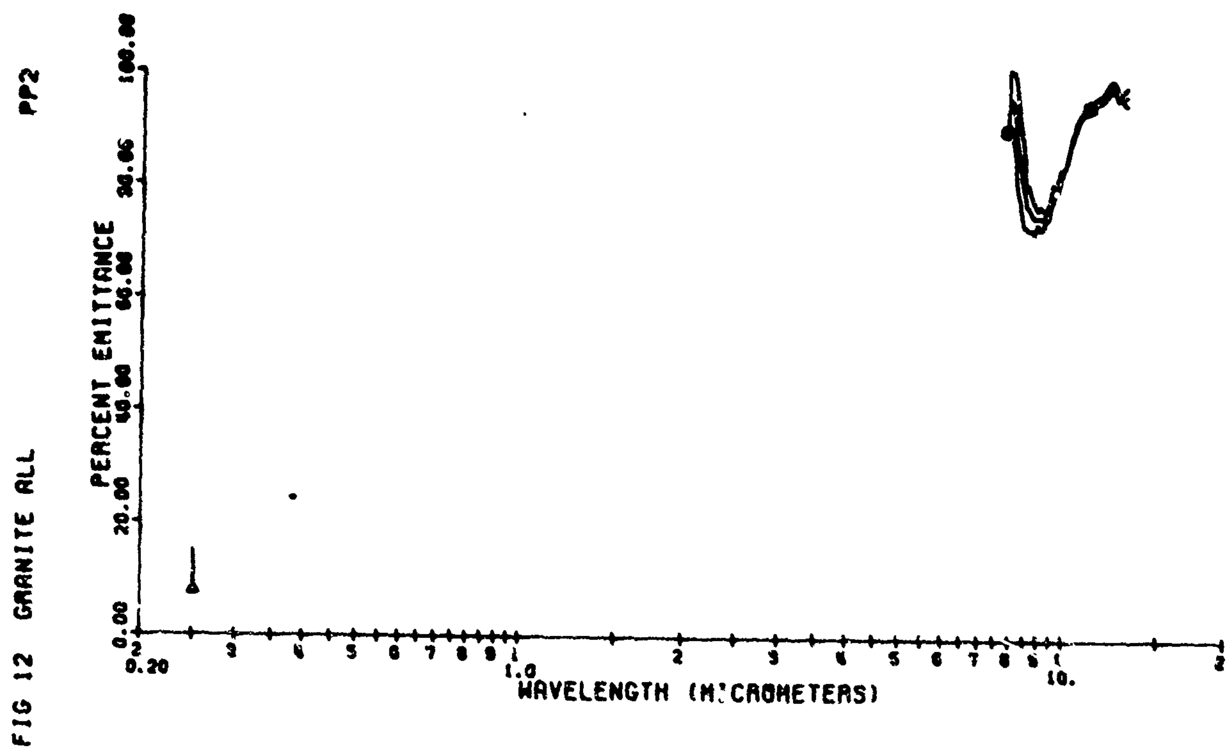


Figure 302. Spectral Emittance of Granite

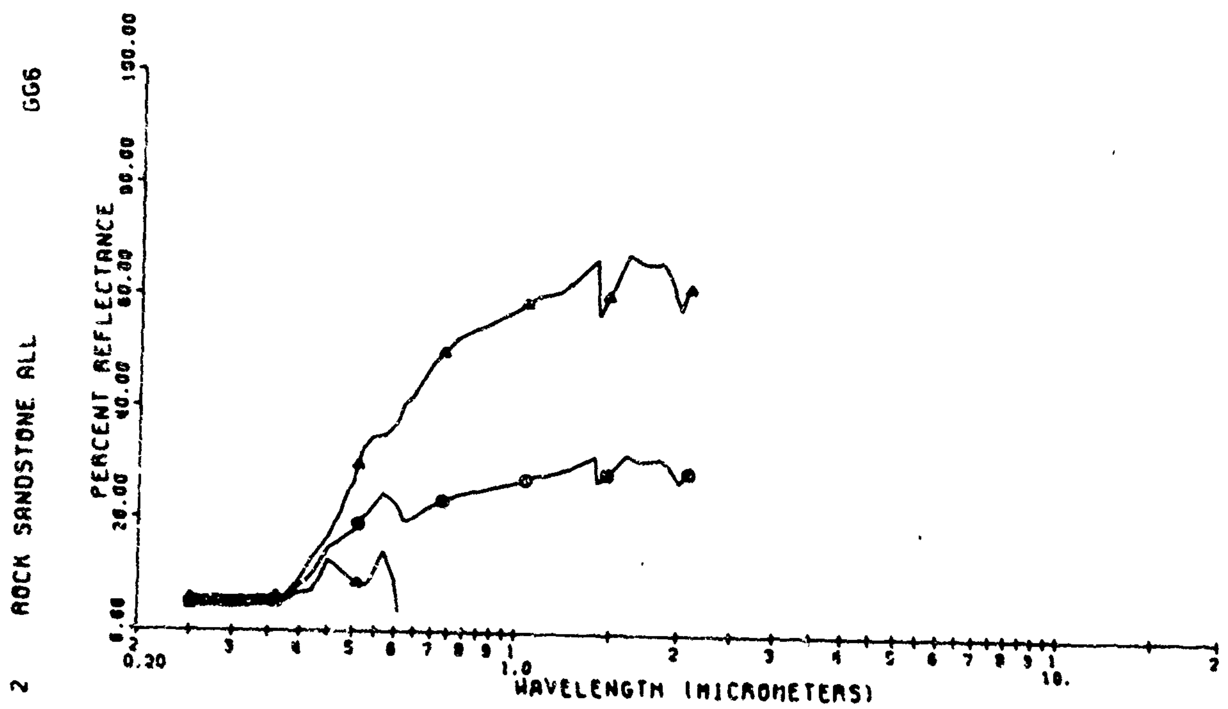


Figure 303. Spectral Reflectance of Sandstone

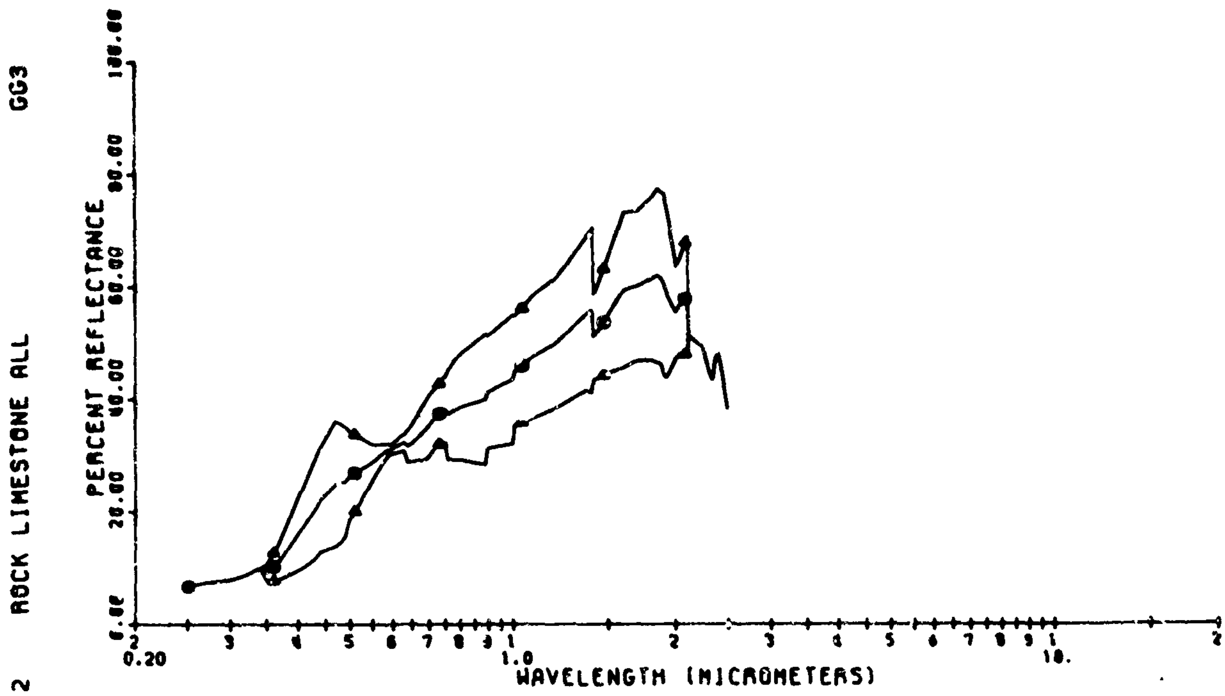


Figure 304. Spectral Reflectance of Limestone

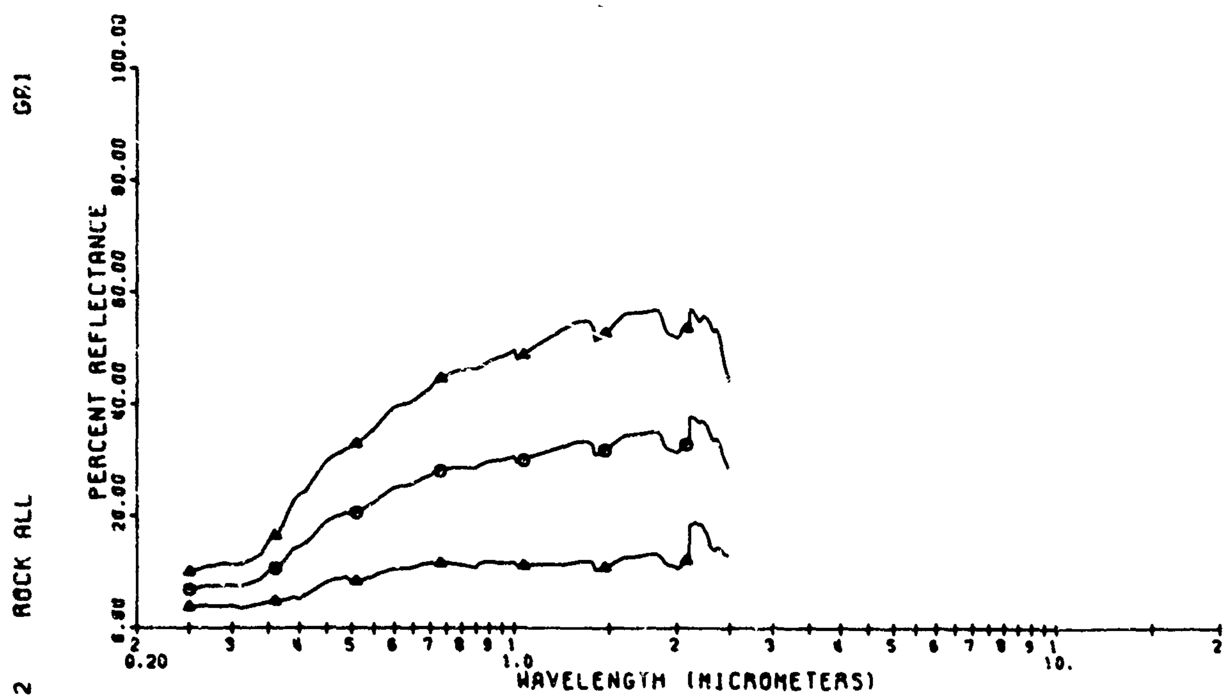


Figure 305. Spectral Reflectance for Many Types of Rocks

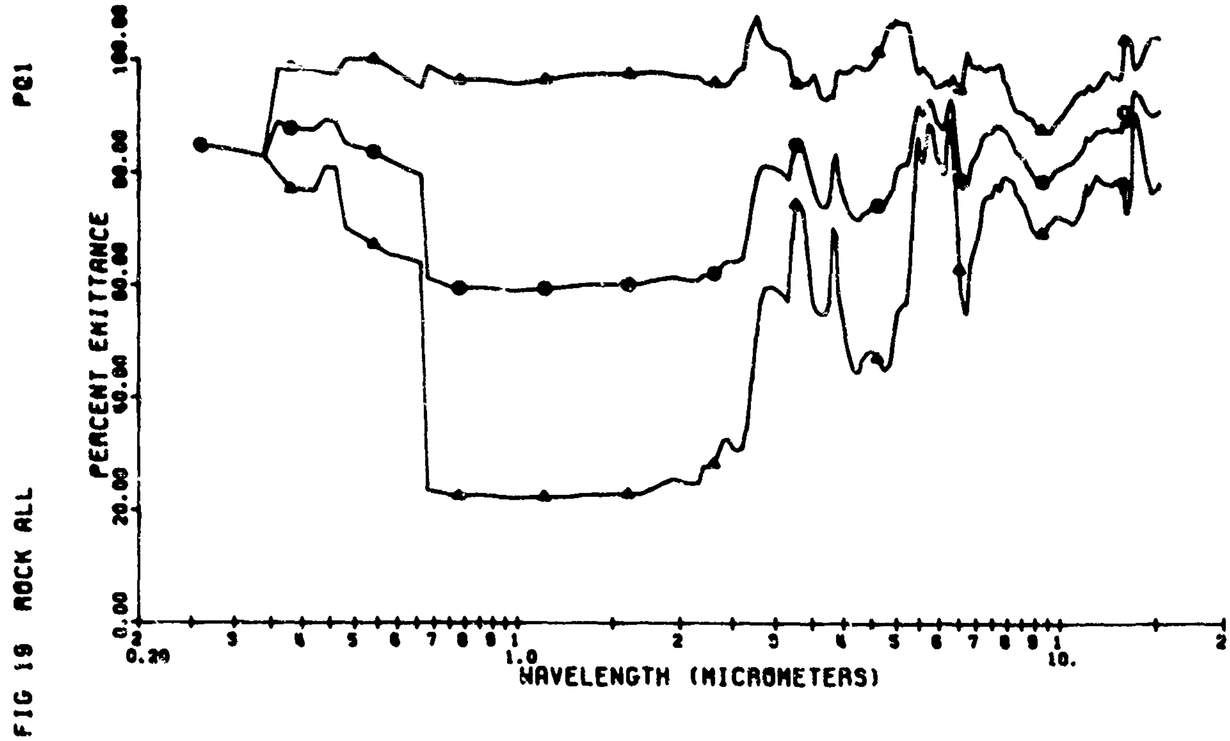


Figure 306. Spectral Emittance for Many Types of Rocks

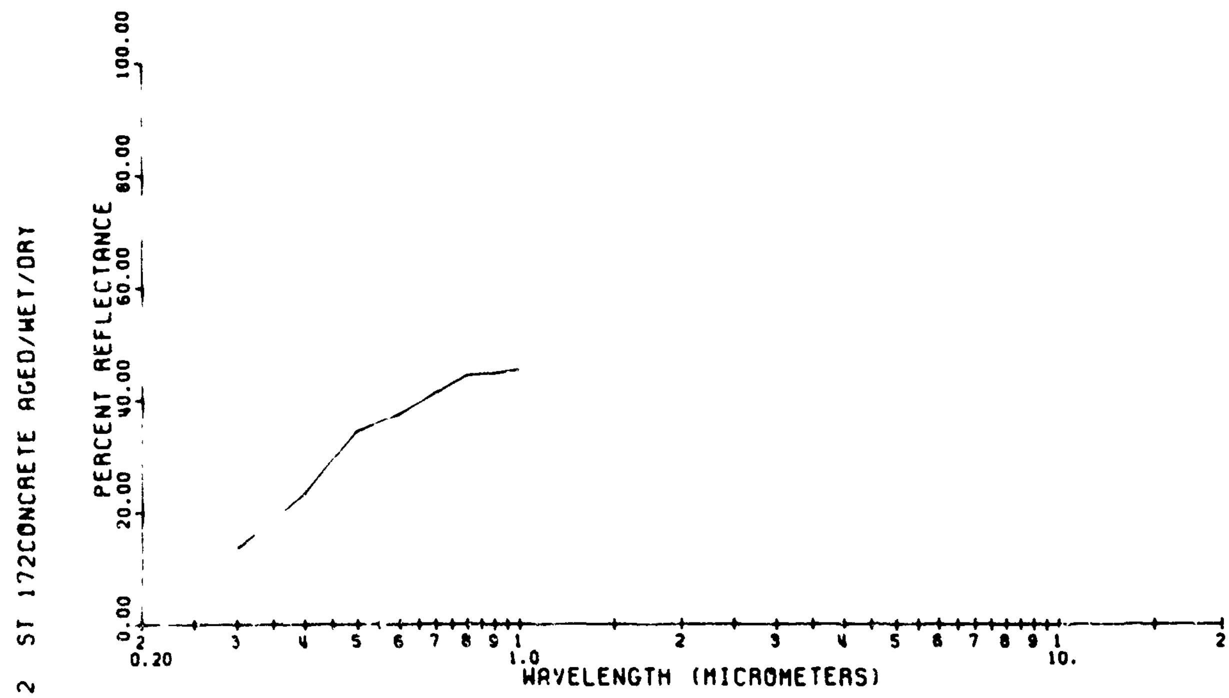


Figure 307. Spectral Reflectance of Aged Concrete

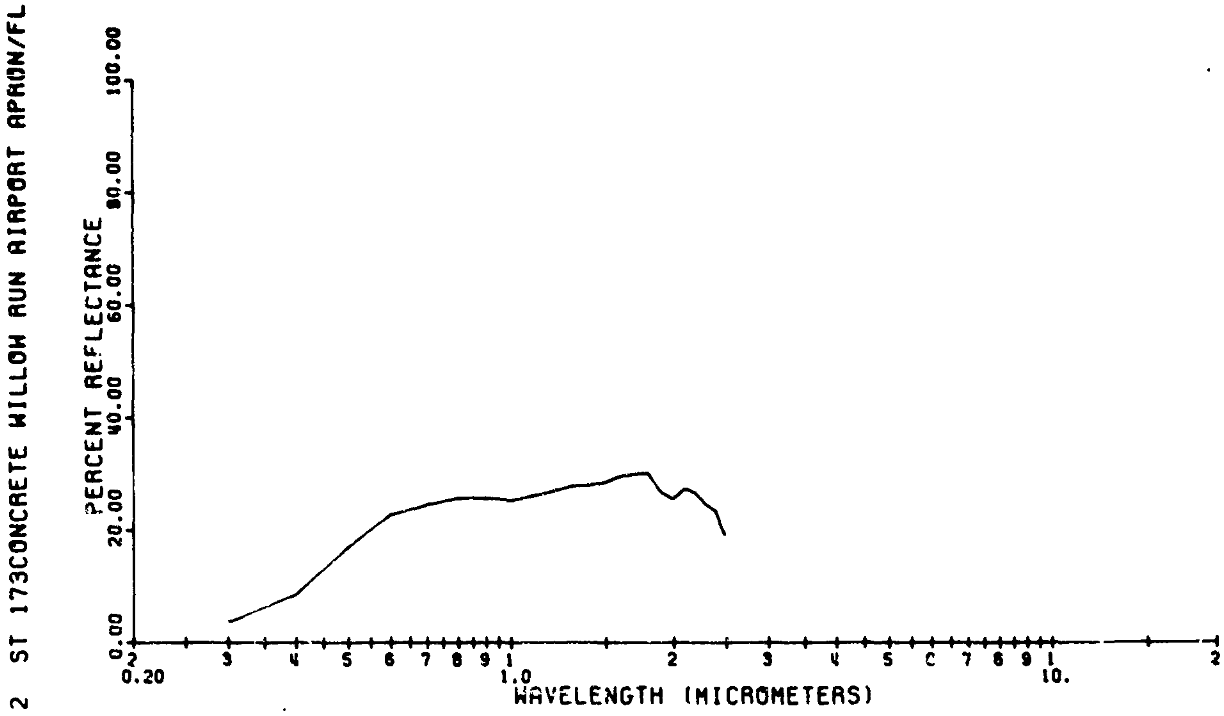


Figure 308. Spectral Reflectance of Concrete Used in an Airport Apron

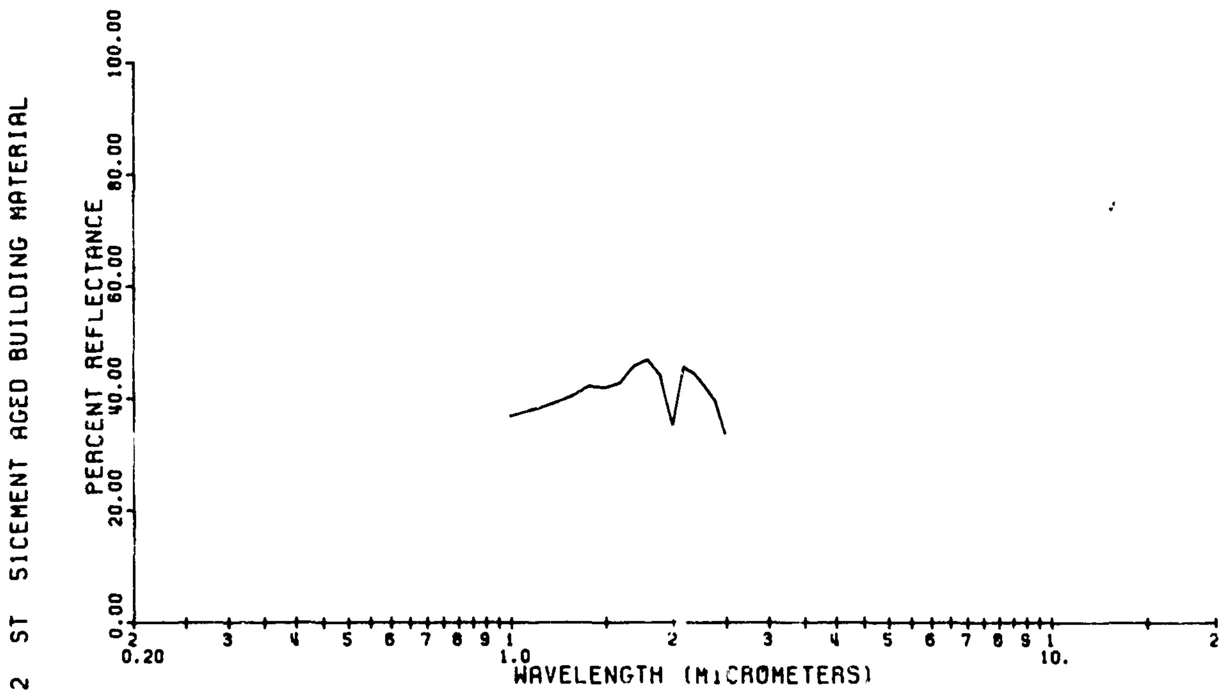


Figure 309. Spectral Reflectance of Cement Used in a Building

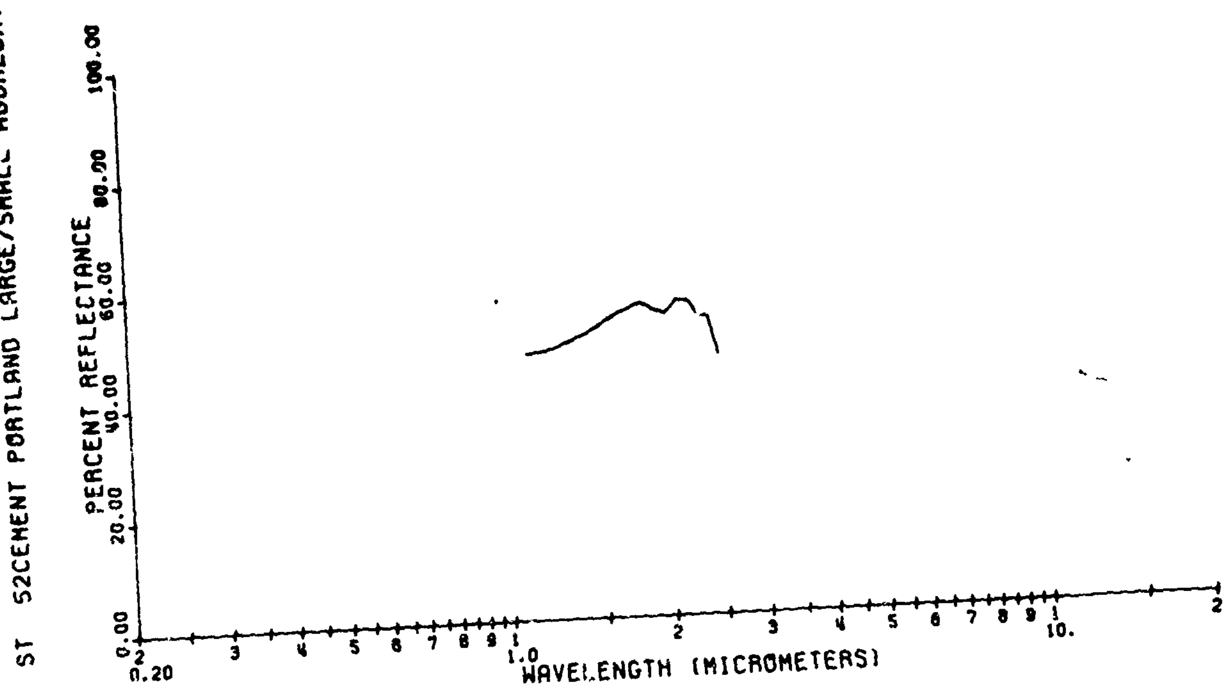


Figure 310. Spectral Reflectance of Portland Cement

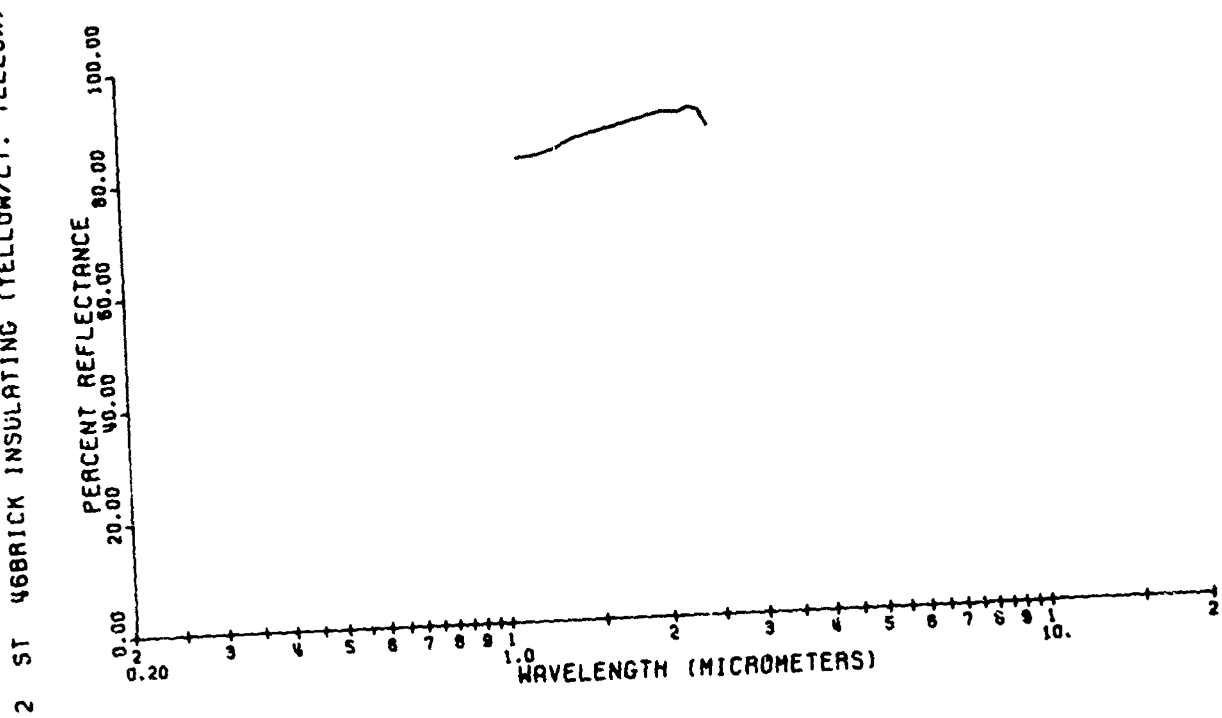


Figure 311. Spectral Reflectance of Light-Yellow Brick

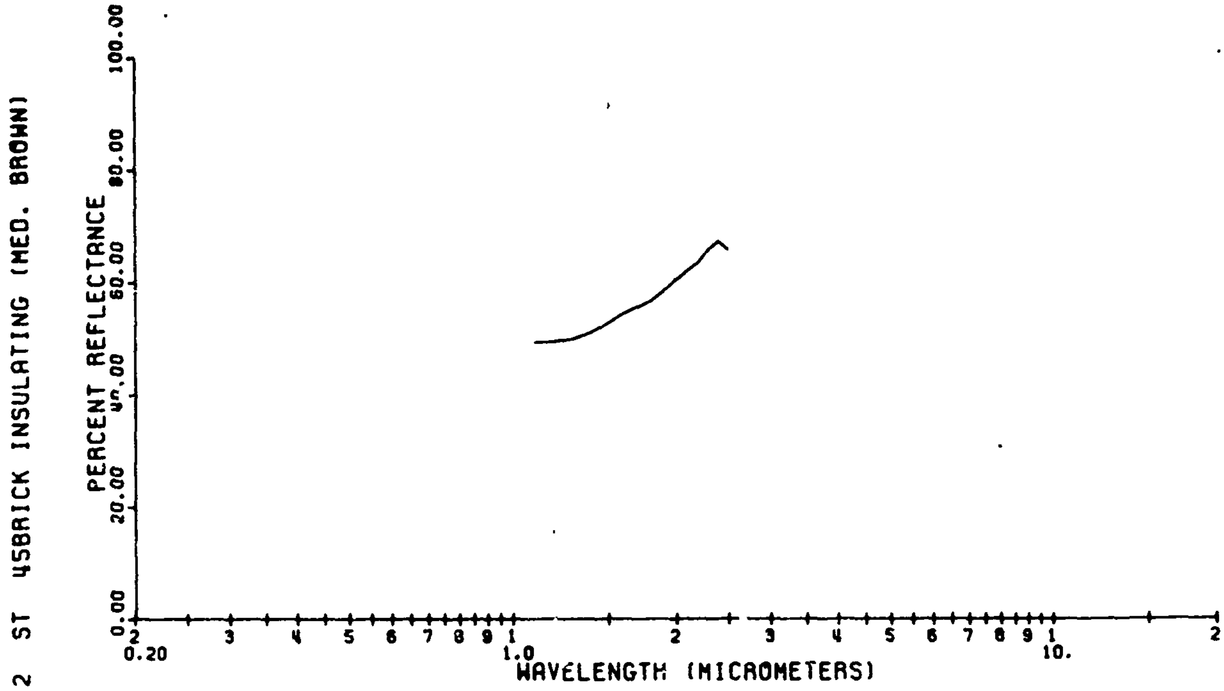


Figure 312. Spectral Reflectance of Medium Brown Brick

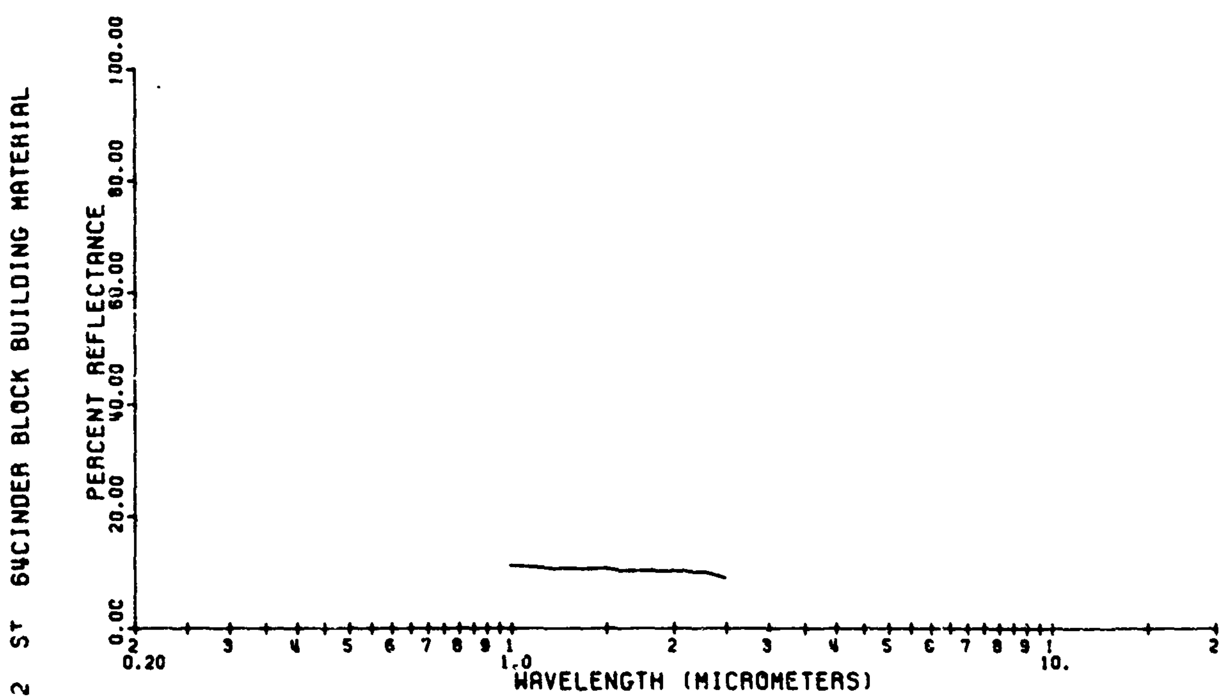


Figure 313. Spectral Reflectance of Cinder Block

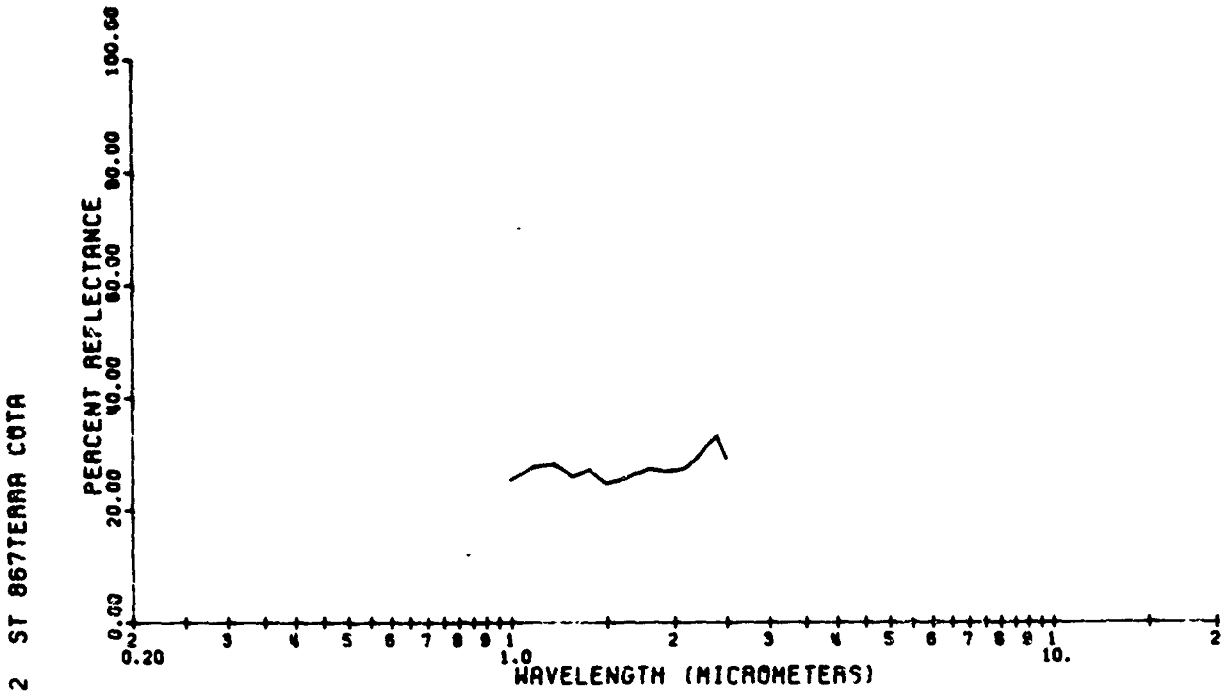


Figure 314. Spectral Reflectance of Terra Cota

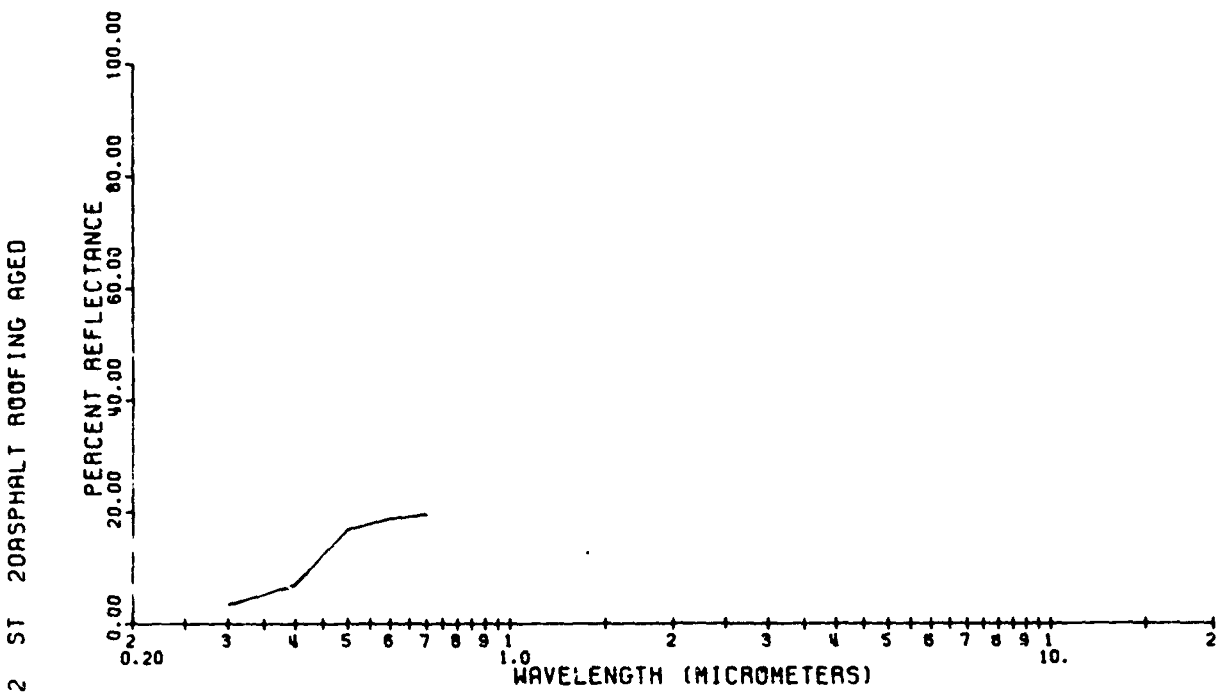


Figure 315. Spectral Reflectance of an Aged Asphalt Base Shingle Roof (Reddish-Brown)

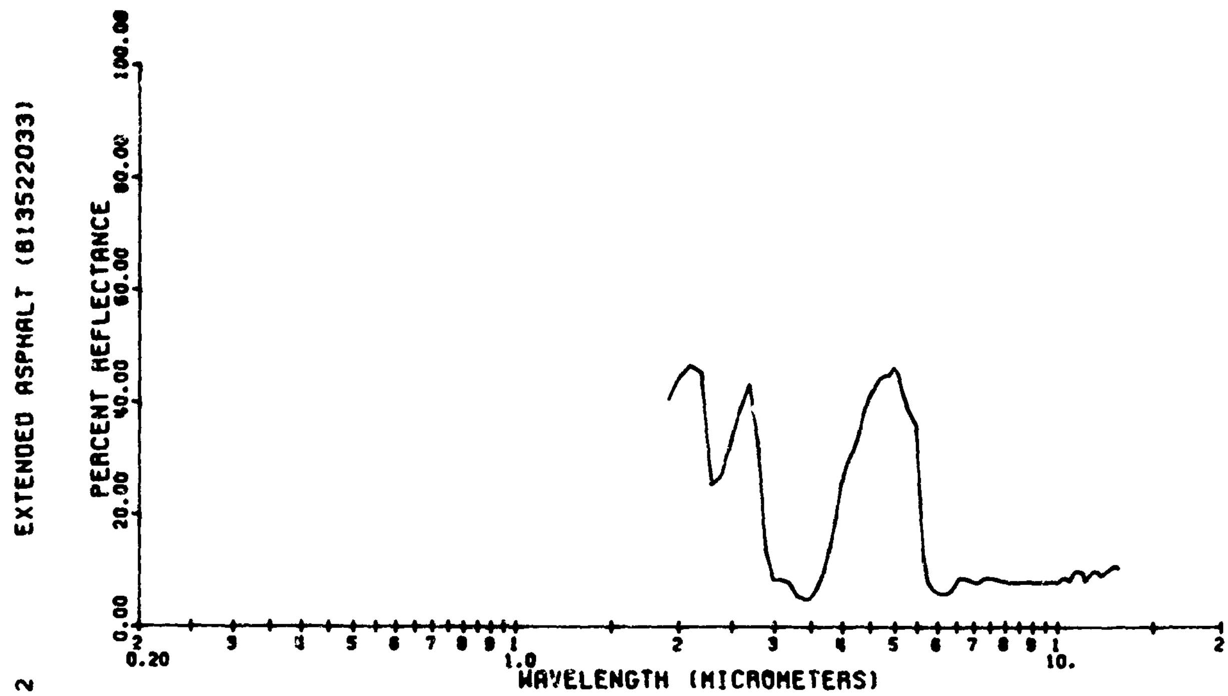


Figure 316. Spectral Reflectance of Asphalt Road

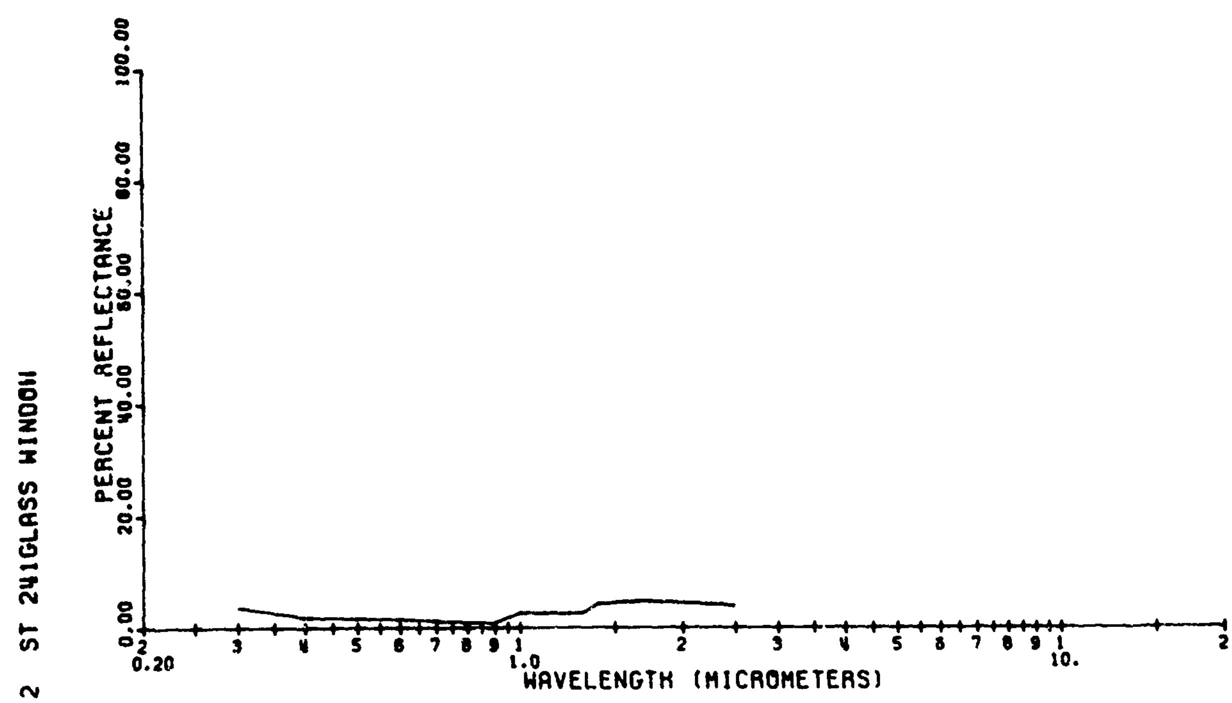


Figure 317. Spectral Reflectance of Glass

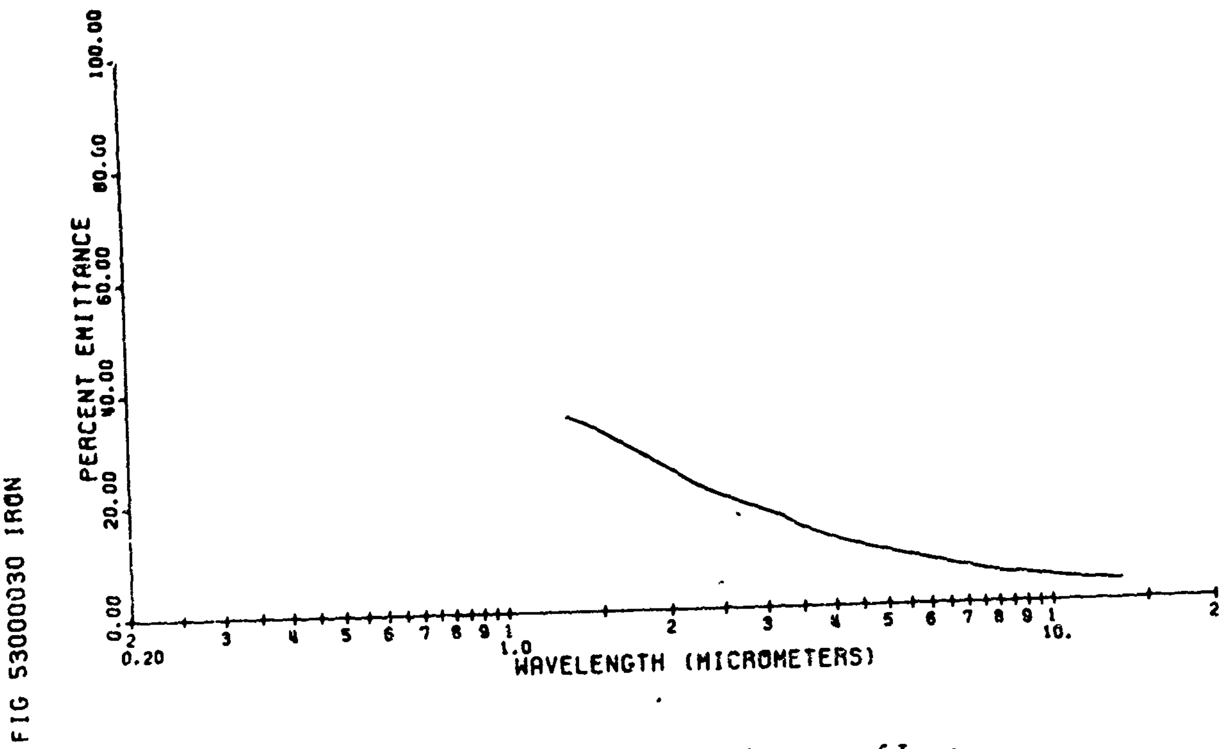


Figure 318. Spectral Emittance of Iron

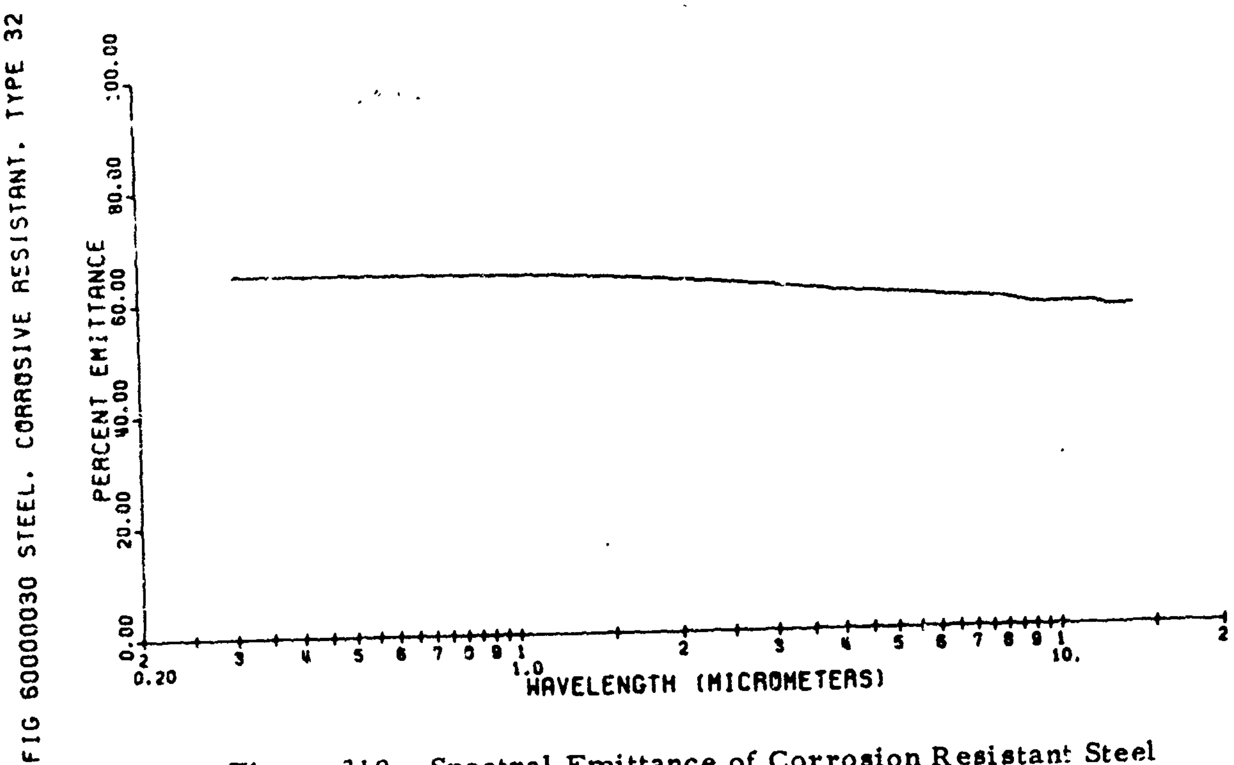


Figure 319. Spectral Emittance of Corrosion Resistant Steel

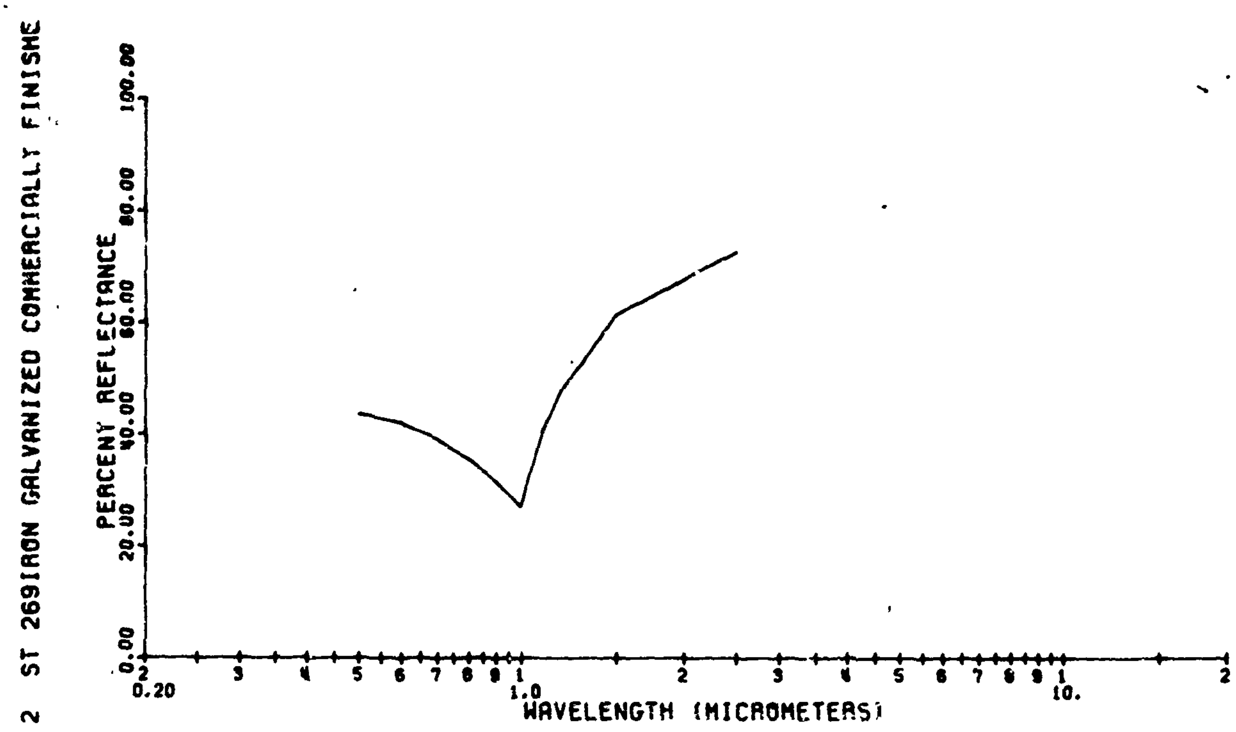


Figure 320. Spectral Reflectance of Galvanized Iron

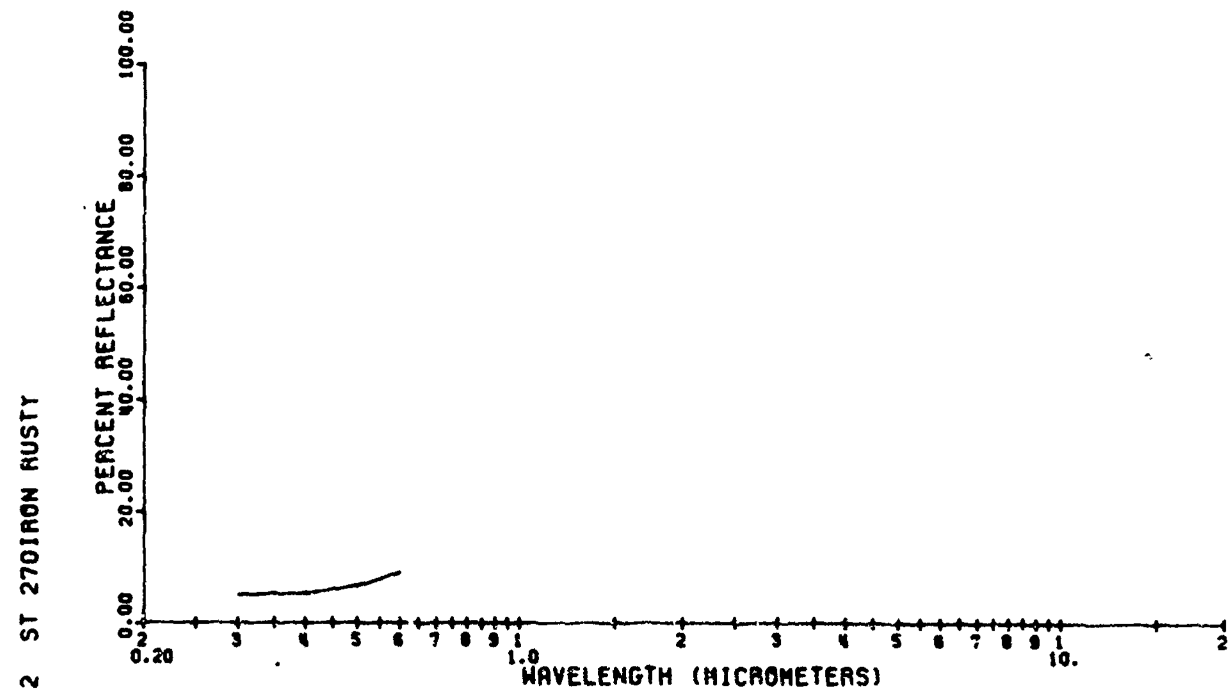


Figure 321. Spectral Reflectance of Rusty Iron

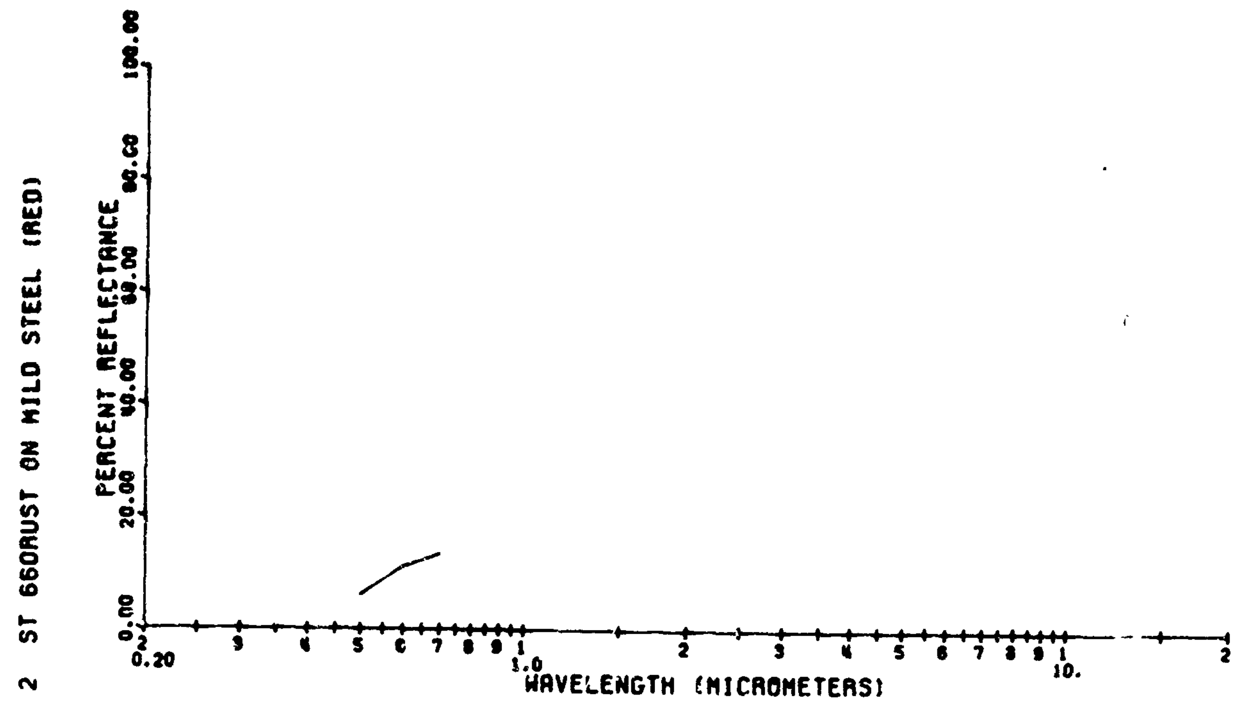


Figure 322. Spectral Reflectance of Rusty Steel

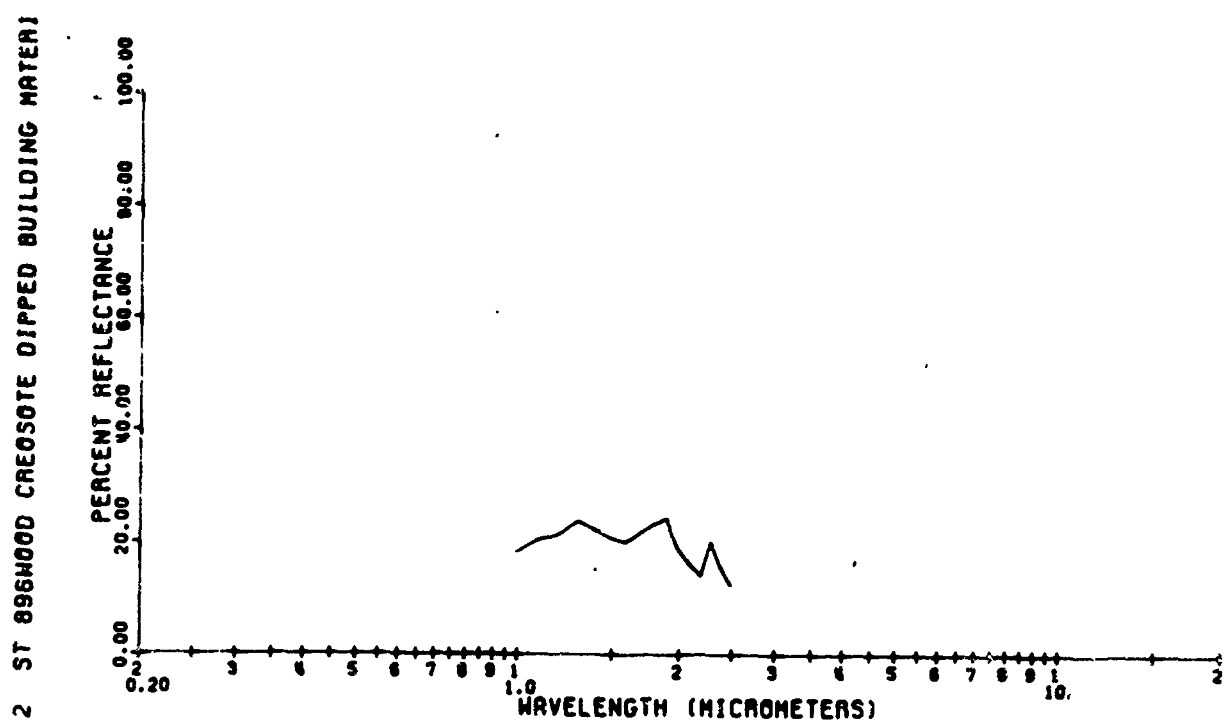


Figure 323. Spectral Reflectance of Cresote Dipped Building Material

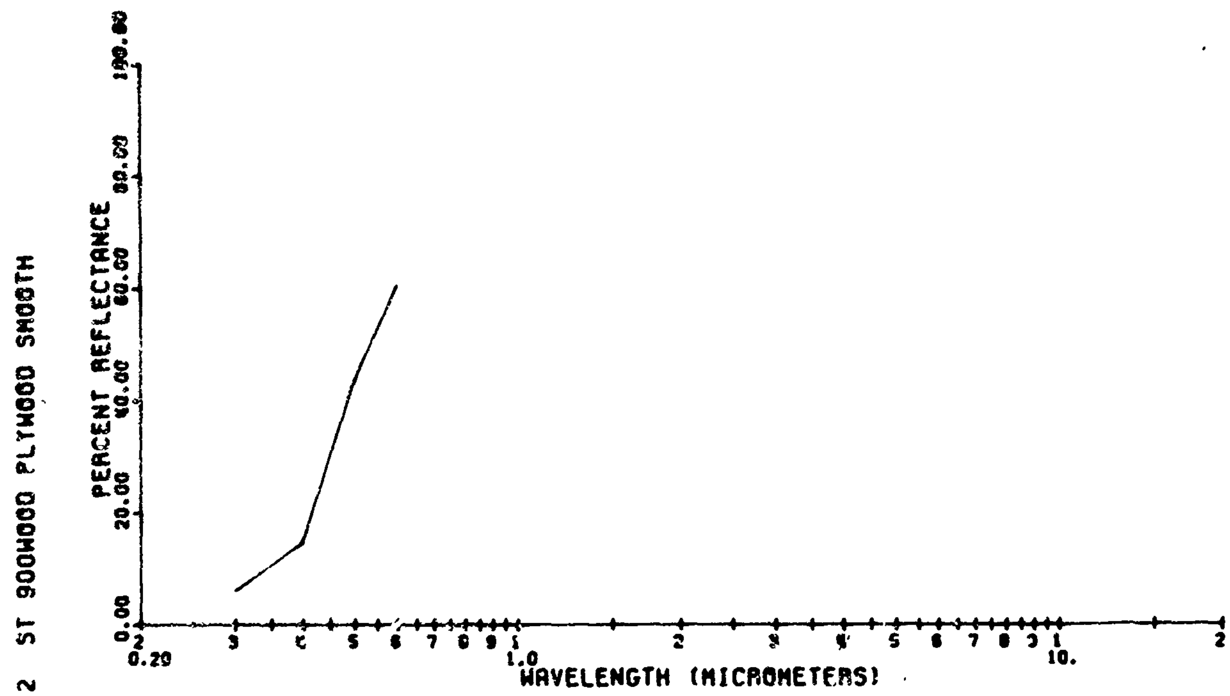


Figure 324. Spectral Reflectance of Freshly Sanded Plywood

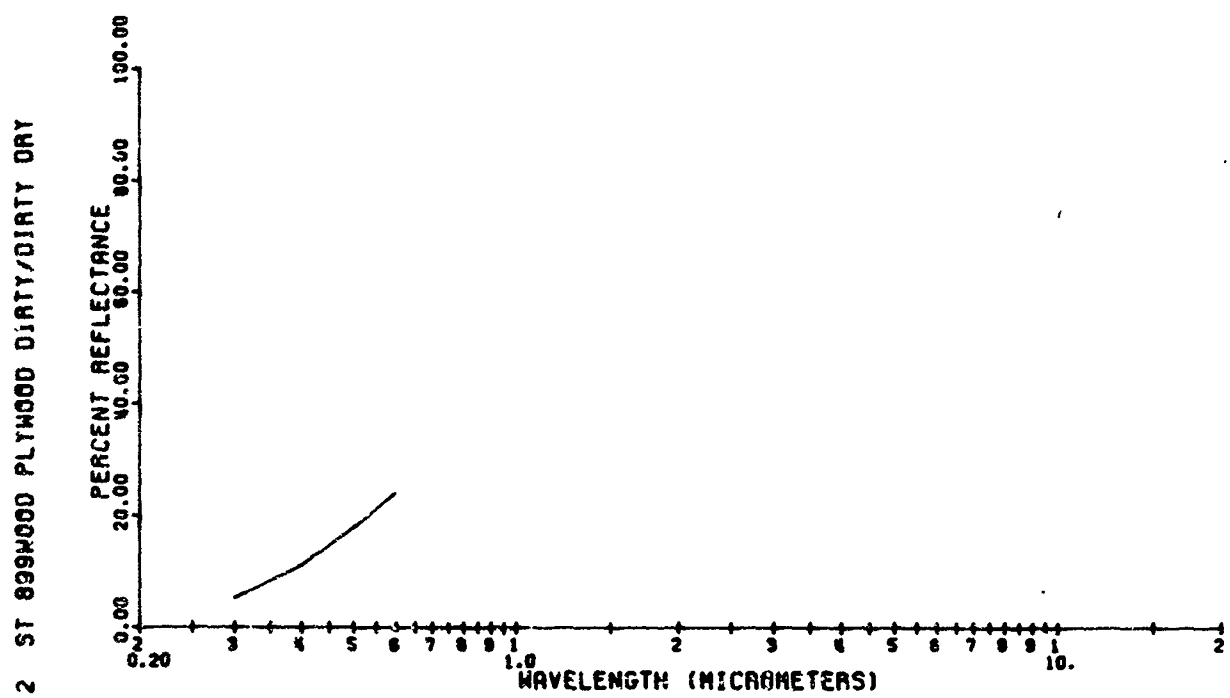


Figure 325. Spectral Reflectance of Dirty Plywood

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